18 PLANNING REPORT

Productivity Impacts of NBS Research: The Development and Diffusion of FMS Technology

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PRODUCTIVITY IMPACTS OF NBS RESEARCH: THE DEVELOPMENT AND DIFFUSION OF FMS TECHNOLOGY

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1

INTRODUCTION

Considerable attention has recently been focused on automated production technology. In part this attention is undoubtedly due to the decline in U.S. productivity growth, increasing inroads that Japanese and European manufacturers have made in capturing a share of American manufacturing markets, and the overall sluggish growth rate of GNP. This focus is also due to the large productivity increases already experienced by manufacturing firms both in the United States and abroad that are attributable to the utilization of the new emerging computer-based automation technologies. For example, robots and computer-aided design systems, already in use in many U.S. firms, provide large productivity benefits and quick payback periods (see Blauth and Preston, 1981 and Krouse, 1981). The prospect of the diffusion of these technologies throughout the manufacturing sector and the integration of robots with numerically controlled machine tools in flexible manufacturing cells promises even greater productivity benefits in the future. The purpose of this report is to assess the role of the National Bureau of Standards in supporting the growth of industrial productivity through its activities in automated production technology.

REPORT OUTLINE

The remainder of this chapter defines the concept of productivity and assesses its importance to the general health of the economy. This chapter also describes the various ways in which productivity benefits can be experienced in the manufacturing sector and the importance of diffusion of automated production technology to its ultimate impacts on productivity. Productivity benefits can be manifested not only in labor cost savings, but also in higher output rates, greater utilization rates of capital equipment, lower inventory costs, and faster lead times.

Chapter 2 describes the traditional role of NBS in fulfilling its mandate to develop infratechnologies and to conduct generic technology research. Infratechnologies include the measurement and standards work which underlie industrial production. Generic technology research is the base of scientific knowledge from which proprietary applications can be drawn. Chapter 2 also describes how these dual roles of NBS are well suited to correct instances of market failure in industry.

The third chapter describes the concept of Flexible Manufacturing Systems (FMS) and its components. These are computer-controlled machine tools and programmable robots connected by a complex central system and a materials handling and storage system. The chapter describes the mechanism by which sophisticated measurement equipment and sensor devices continuously feed data to one or more computers, which respond in real time to sensory inputs and alter their commands appropriately. Chapter 3 also describes the productivity benefits of Flexible Manufacturing Systems and its components, as well as the nature of the industries which have developed these technologies. Some of these benefits are realized simply by retrofitting robots in existing plants or by purchasing and using advanced Numerically Controlled (NC) systems, robots, or coordinate measuring machines. Additional benefits which are derived from the integration of the system are also discussed.

Chapter 4 describes both the current state of technological development and the current uses of automated production technology in American manufacturing. Computer control of NC machines has been commercially available for over 10 years. In addition, there are currently thousands of "dumb" robots being used in the manufacturing sector. However, the individual functions of processing, assembly, inspection, and materials handling and transport have yet to be integrated into a consolidated system under complex computer control. This chapter also describes the general direction in which this technology is moving. As we shall see, the further development and use of Flexible Manufacturing Systems require research in:

- Measurement-based sensors;
- Interface standards; and
- Complex control by a hierarchy of computers.

This characterization of the evolutionary patterns of flexible manufacturing technologies leads to a search for market failures that are typical in the development and diffusion of new technologies.

The fifth chapter describes the research NBS is undertaking in its Automated Manufacturing Research Facility (AMRF). This chapter describes the AMRF facility as well as NBS research on interface standards and measurement done there. Finally, Chapter 5 describes the ways in which NBS research in automated production technology might affect the diffusion (and thus the ultimate productivity impacts) of these emerging technologies.

Because of the importance of the diffusion of industrial innovation to its ultimate productivity impacts, Chapter 6 describes the early economic and econometric literature on diffusion as well as its criticisms. This literature typically estimates the impact of various factors -- technological, industrial, and environmental -- on the speed of diffusion.

Chapter 7 discusses managerial and other factors internal to the firm which affect the speed of diffusion. The importance of external factors such as the intensity of international competition is also assessed. The final chapter assesses the various determinants of the speed of diffusion and the role NBS might play in encouraging overall industrial productivity by aiding the diffusion process.

INDUSTRIAL PRODUCTIVITY AND ITS IMPACTS

The simplest definition of productivity is real output produced per unit of input. When only labor inputs are measured, the resultant figure is labor productivity. The Labor Department regularly publishes statistics on average labor productivity in the U.S. economy and in subsectors of the economy. Real output per manhour in the nonfarm business sector rose at an annual rate of 3.0 percent during the period 1960 to 1967, 2.1 percent over the years 1967 to 1973, and only 1.2 percent from 1973 to 1977. Since 1977 there has been very little improvement in productivity (see Economic Report of the President, 1983). Since labor is only one factor of production (although by value the most important), a better measure of productivity would also take into account the relative contributions of capital, raw materials, and intermediate goods. When real output is divided by the weighted contributions of all associated inputs, the resulting statistic is total factor productivity. Historical measurements of rates of increase in total factor productivity yield similar results to those for labor productivity reported above. Kendrick and Grossman report an annual growth of total factor productivity of 3.4 percent during the years 1960 to 1966, dropping to 0.8 percent during the years 1973 to 1978, the last period reported (Kendrick and Grossman, Productivity in the United States, 1980).

Although economists are understandably concerned with published statistics on productivity, the press and public seem even more concerned with inflation and the inroads made by imports in domestic markets for manufacturing goods. Much attention is focused on automobile and steel markets, but the Japanese have also made large inroads in audio equipment, cameras, calculators, watches, semiconductors, and office equipment. The increased degree of foreign competition is undoubtedly due, in part, to a decline in the rate of U.S. productivity growth relative to that of its major foreign competitors.

Whether one focuses on published statistics on labor productivity, market shares achieved by foreign producers, or the sluggish rate of growth in overall economic activity in recent years, it is generally agreed that the U.S. economy has a "productivity problem." Most economists agree that the primary source of productivity growth is advances in knowledge, both technological and managerial. Technological knowledge includes the physical properties of substances and how to make, combine, and use them to achieve commercially useful results. Advances in knowledge, often resulting from sustained research and development activity, are usually manifested in innovation. Innovation can be of two kinds, product and process. While product innovation usually results in new and different products or products with improved characteristics, process innovation results in the ability to produce the same product at a lower unit cost. In order to examine, measure, or explain the productivity benefits of NBS research in automated production technology, it is instructive to examine more closely the ways in which productivity increases manifest themselves in the manufacturing sector.

The productivity benefits resulting from process innovation can usually be measured by examining the cost savings enjoyed in making the same product with fewer or less valuable productive resources. The measurement of productivity benefits resulting from product innovations is more difficult, particularly when the new product is a final good with very different characteristics from other consumer goods. Fortunately, this measurement problem need not concern us, since the productivity impacts of automated production technology are likely to appear in intermediate, rather than final, goods. With intermediate goods, cost savings can be expected to appear at the next stage of production. For example, the introduction of a robot, although considered a new product by robot manufacturers, is considered a process innovation by industrial users and can be expected to provide cost savings to these users.

In the manufacturing sector, productivity impacts can assume a number of forms. Most can be seen in terms of reductions in labor, capital, or raw materials requirements, or reductions in inventory costs. The simplest and most straightforward productivity benefit occurs when labor costs are reduced. For example, the introduction of one or more robots in the manufacturing environment is likely to lead to reductions in labor requirements. Labor cost savings may take the form of a reduction in the number of labor hours required, a reduction in certain skill levels or training costs of labor, or a combination of the two. Provided that the properly calculated depreciation, interest, and maintenance costs of a robot fall short of the savings in labor costs, cost savings and a gain in productivity result from the introduction of the robot.

Savings in raw materials costs might result, for example, if spray painting done by robots requires less paint than the corresponding job performed with human labor. Because productivity increases result from advances in knowledge, much of which may be embodied in new capital equipment, these productivity increases may take the form of a substitution of capital for labor. A robot is perhaps the best example of this phenomenon. However, savings in the use of capital equipment may also be realized by innovation in the manufacturing process itself. For example, machine tools are usually left idle when machine parts are being measured, when tools are being changed, and during holidays, strikes, and when there is no second or third shift. If the introduction of automation allows faster measurement and tool changes, as well as an overall higher level of utilization of machines, the average costs for usage of these machines will decline. Similarly, if automation facilitates a higher level of machine utilization and a more timely flow of materials and parts through the manufacturing workplace, inventory cost savings are likely to be realized.

It is also possible to realize productivity benefits that cannot easily be placed in a framework of cost savings of labor, capital, raw materials, or inventory. Most prominent among these benefits are quality improvements, reductions in the costs of transacting between buyers and sellers, more competitive markets, and dynamic benefits such as shorter manufacturing lead times.

Improvements in the quality of products produced through automation may take a number of forms. The simplest form of quality improvement is analytically equivalent to simple cost reduction. That is, improvements in the quality or accuracy of the manufacturing process may lead to a higher yield of products which satisfy quality control tests. Thus, quality improvements can lead to the production of the same output with fewer units of input. For example, if parts must be machined to a given level of tolerance and machining accuracy is improved, then a higher proportion of parts will be acceptable, thus lowering the average costs of machined parts.

Improvements in quality may also take the form of superior product characteristics, including greater reliability, durability, or other characteristics valued in the marketplace. The productivity benefit of this type of quality improvement might be measured by examining the increased value to consumers of the improvement in these product characteristics.

Another area of technical knowledge which results in productivity benefits difficult to quantify is the reduction in transactions costs between buyers and sellers of products. If complicated machinery or parts are being sold, precise characterization of dimensions and geometric properties is necessary. Technical knowledge in the form of standardized means and methods of measurement for precision-machined parts and for machines that do cutting and measuring is essential. Agreements between buyers and sellers as to the means and methods of measurement can save the often considerable expense of resolving misunderstandings concerning the characteristics of traded products.

Agreement between buyers and sellers may also produce productivity benefits in the form of reductions in design costs. For example, if the seller and purchaser of an intermediate good were to have access to the same database describing precisely the properties of the part being traded, design costs as well as the costs of error might be reduced. The Initial Graphics Exchange Specification (IGES) is a set of standards that facilitates communication between different computer-aided design systems. This enables a manufacturer to furnish its supplier with the database describing a part to be manufactured, thus eliminating design costs and error costs. IGES also permits communication between a CAD system and a CAM system.

Agreements or standards among vendors concerning the means of characterizing parts may also lead to a greater degree of competition. These standard interfaces can be more narrow in scope, such as IGES, which facilitates communication among CAD systems, or exceedingly broad in scope, facilitating communication among the software used to control machine tools, robots, and other parts of an automated manufacturing system. Standards ensure compatibility among the various parts of a system, and may facilitate the entry and competition of new vendors that are too small to enter more than one market simultaneously. Without software compatibility, small producers may be reluctant to enter any one market, because potential buyers may be locked into current suppliers of the entire system. The benefits of increased competition are both well known and difficult to quantify. Competition usually results in lower prices and may facilitate innovation as well. Increased innovation is particularly likely if entry of small innovative firms is facilitated by the knowledge that their new and improved products will be compatible with the rest of an automated system.

Another, more dynamic manifestation of productivity benefits occurs when the entire design, manufacturing, and testing process is accelerated. Particularly when there are distinct advantages to being first in the market and when there is learning by doing, the first manufacturer (or country) producing a new product may attain a commanding lead in a growing market. Learning by doing means that as one produces more output, learning takes place that leads to lower production costs with cumulative production experience. The first entrant in the market has a potential cost advantage over rivals or potential rivals, particularly when the market leader prices at a low level relative to cost, thus encouraging the development of a large and growing market, and hence more "learning." If product differentiation is present, being a first or at least early entrant in a new market can also be important. This is particularly true for foreign competitors. It took many years for imported Japanese products to gain acceptance by the American consumer. Maintaining (or increasing) their market share has been achieved much more quickly by the Japanese.

The ability to respond quickly to new technical opportunities and consumer preferences can yield long-term benefits to firms that are early entrants, particularly when there is learning by doing. Since the diffusion of technology or learning may be slower across countries than across firms or industries within a country, this benefit may accrue to a whole country. The ability to capture and sustain a large share of a new and growing market as a result of the wise use of technical information is also a productivity benefit, although one not as easily quantifiable as simple cost reductions, quality increases, or reductions in transactions cost.

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NBS RESEARCH

NBS ROLES

NBS plays two primary roles in supporting industrial innovation and productivity growth (Charles River Associates, 1983). These shall be referred to as the "infratechnology research" and the "generic technology research" roles. This chapter will define these roles and illustrate how they serve to influence manufacturing productivity both directly and indirectly through their impacts on private R&D activity.

THE INFRATECHNOLOGY RESEARCH ROLE

Infratechnology can be defined to include methods and basic data for R&D, product and process design, production, and marketing (Tassey, 1982a). Examples of infratechnologies include standards, measurement methods, and reference data characterizing properties of materials; these allow firms to draw more effectively on the underlying base of scientific and technological knowledge. The primary role played by NBS in supporting industrial innovation and productivity growth involves the conduct of research aimed at advancing such infratechnologies (Tassey, 1982b). This NBS role is mandated by the NBS Organic Act (1901), which specifically empowers NBS to undertake the following activities:

> (a) The custody, maintenance, and development of the national standards of measurement, and the provision of means and methods for making measurements consistent with those standards, including the comparison of standards used in scientific investigations,

> *engineering*, *manufacturing*, *commerce*, and educational institutions, with the standards adopted or recognized by the Government.
>
> (b) The determination of physical constants and properties of materials when such data are of great importance to scientific or *manufacturing* interests and are not to be obtained of sufficient accuracy elsewhere. (National Bureau of Standards, 1980, Appendix B, *emphasis added*.)

By providing means, methods, and basic data for measurement, infratechnology research serves to reduce costs at all stages of the economic process. For example, more accurate measurement may reduce design costs by permitting a reduction in the need to overspecify the performance parameters of a system in order to accommodate a tolerance for measurement error. Improved measurement techniques may allow for quicker, more efficient testing of new designs. Infratechnologies may similarly serve to improve yields and decrease costs at the manufacturing stage. For example, the availability of standard reference data on materials can help firms to gain increased control over processes involving the production or use in production of these materials. Infratechnologies may also serve to lower transactions costs involved in the marketing and transfer of products. Measurement standards can in many cases serve to increase the ease and lower the cost to buyers and sellers of reaching agreement on how acceptance testing is to be done.

THE GENERIC TECHNOLOGY RESEARCH ROLE

The generic technology underlying an industry can be defined as the base of scientific and technological *knowledge* from which proprietary applications can be drawn. Generic technology research, then, is defined to include research directed toward the discovery of the basic scientific and technological principles underlying a technology or the performance of a function. In the course of performing its basic mission as the nation's central standards and measurement laboratory, NBS frequently undertakes generic technology research. To a large extent, such research is performed in order for NBS to develop the technical competence (expertise plus facilities) required to play an infratechnology role in a technical area in which NBS has no prior experience.

Generic technology research may help to increase industrial productivity in several ways. First, such research adds to the knowledge base from which private industry draws proprietary applications. In the language of the economics of technical change, such research serves to identify key *technical opportunities*. For example, NBS is currently involved in a program of research into rapid solidification technology, an innovative metallurgical process. As part of this research, NBS is developing rules based on kinetic and thermodynamic theory to allow for prediction and control of important processes. This information, in the form of alloy phase diagrams, is expected to provide the producers of rapidly solidified materials with basic information and predictive models, by which more efficient choices of materials can be made, optimal compositions can be selected, and processing conditions can be improved in order to obtain desirable alloy properties.

Demonstration of technical opportunities may serve to affect industrial innovation and productivity growth in two ways. First, the level of technical opportunities available to the firms in an industry is generally thought to be one of the more important exogenous factors influencing the level of R&D undertaken by those firms (Levin and Reiss, 1981). Thus, increases in technical opportunities induced by generic technology research are expected to increase the level of R&D undertaken by an industry, ceteris paribus. Second, the demonstration of technical opportunities in a new area of technology in which technical uncertainties had previously been substantial may serve to reduce the cost of capital for firms exploring that area. Such reductions in the cost of R&D are expected to increase further the level of R&D performed in an industry. As R&D activity can be viewed as an investment in future productivity, generic technology research or research directed at augmenting and advancing the knowledge base underlying a technology will have an (indirect) effect on industrial productivity.

MARKET FAILURE

In the previous section, it was noted that both infratechnology and generic technology are important to the development of new products and processes and ultimately to the advancement of industrial productivity. Yet despite their importance to industry, there is reason to believe that the private sector will underinvest in infratechnology and in certain types of generic technology research in the absence of public support. The factors underlying such market failure include the inability of firms to capture a significant fraction of the returns to research in these areas, the long-term and high-risk nature of the research, and (often) the requirement of specialized resources and expertise that cannot be fully utilized by individual firms or even industries.

Arrow (1962) pointed out that the knowledge produced by industrial research and development has many of the attributes of a public good. This implies that it is difficult for an individual firm to capture fully the returns to R&D. Thus, the social value of the additions to the knowledge base generated by R&D (which include its value to other firms in the same industry and firms in other industries as well as to consumers) will generally exceed the value of the knowledge to the firm doing the R&D. Where this gap between social and private value is great, the possibility exists that socially beneficial R&D will not be undertaken by individual firms. This underinvestment will take place where investments in R&D have ex-ante, risk-adjusted private rates of return that are less than the opportunity cost of capital, but where the social rate of return exceeds the cost of capital.

This gap between the social and private value of R&D is expected to be particularly great in the areas of infratechnology and generic technology research. These types of research are expected to generate knowledge the applications of which are more likely to transcend firm and even industry boundaries than is more proprietary research directed at specific product and process applications. That is, the potential benefits of these kinds of research are likely to be more far-reaching than those of applied research. Moreover, it may be more difficult to appropriate the returns to these types of research, as general knowledge transfers across firms more readily than specific applied knowledge.

Infratechnology research and especially generic technology research can be characterized as relatively long-term in nature. Moreover, generic technology research is expected to involve greater levels of "risk" or uncertainty regarding its outcome than applied research projects. It has been suggested in the economics literature that competition will force firms to invest in R&D that offers relatively quick and certain returns, even when this means passing up projects that are potentially more rewarding in the long run (e.g., see Dasgupta and Stiglitz, 1980). As a result, it is expected that industry will often forego certain infratechnology and generic technology research that offers high potential returns, even when such returns are appropriable, due to the long-term and risky nature of the research.

Both infratechnology and generic technology research may require specialized research facilities and staff experience. For example, the efficient conduct of research into the means and methods underlying industrial measurement and measurement standards requires a research staff with specific expertise in metrology, the science of measurement. Similarly, research into the scientific and technological principles underlying a complex technology may require a capital-intensive research facility. Thus, in some cases, the minimum efficient scale required for research may exceed the minimum efficient scale required for manufacturing in related industries. In such cases it is unlikely that individual firms, and possibly individual industries, would be able to fully or efficiently employ the specialized staff or facilities. This would imply that the cost of such research would be higher if done in a decentralized fashion. As a result, there can be a gap between the social rate of return of research performed in a single, central (government) laboratory and the social rate from research performed in a series of decentralized private labs. If the individual private rates are too low (or if the sum of the private rates is even too low to justify a joint venture), underinvestment will result.

Finally, standards often require a substantial degree of agreement among competing firms in order to be effective. Such agreement may be difficult to achieve as firms attempt to design standards so as to protect or enhance their own competitive interests. Moreover, to the extent that firms in an industry are reluctant to accept the technical input of other firms into the standards-setting process, there may be little incentive for firms to undertake research aimed explicitly at providing the technical basis for a standard.

Thus, where the output of research is not appropriable by the individual firm, where research is long-term and risky in nature, where research requires specialized facilities and staff, and where agreement among competing firms is essential, the social rate of return is likely to exceed the private rate by a substantial amount and the private rate may be too low to bring forth the socially desirable rate of investment. In investment projects where the social rate exceeds the cost of capital but where the private rate falls short of the firm's target or hurdle rate of return, underinvestment from society's point of view will result. In the case of infratechnology and generic technology research which characterizes NBS' role, this gap between the social and private value of R&D is expected to be great. Thus, it is especially likely that private underinvestment will occur in the types of research which characterize NBS activity.

NBS RESEARCH

NBS has long been involved in supplying the mechanical manufacturing sector with the "means and methods" for making precise measurements. In the past, the measurement activities of the Center for Manufacturing Engineering (CME) at NBS have been concerned with providing calibration services for mechanical artifact standards such as gauge blocks. These artifacts are currently the basis of the National Measurement System, which has remained essentially unchanged since the 1940s.

Since that time, manufacturing technology has changed dramatically, beginning with the introduction of numerically controlled machine tools and Flexible Manufacturing Systems. The nature of these technologies is such that the quality control systems in the manufacturing sector increasingly depend on characterization of the process, monitoring of machine parameters, and adaptive control (rather than simply measurement of parameters after the process, or a step in the process, was completed). Such a development requires NBS to provide the "means and methods" of measurement where the measurements are deeply embedded in the process.

For the last decade, NBS has been engaged in infratechnology research and generic technology research in many areas, including robotics and robot vision systems, coordinate-measuring machines, and sensor systems. More recently, NBS has embarked on the design, procurement, and installation of a fully-automated manufacturing research facility (AMRF) in support of its measurement and standards responsibilities. When complete, the facility will provide the capabilities of a flexible manufacturing cell. NBS is purchasing the components of the system, such as robots, machine tools, and computers, from various vendors in the marketplace. The facility will function as a "test bed" for developing "means and methods" of doing precise measurements needed by an integrated manufacturing system.

The automated manufacturing research facility will focus on areas where economic theory indicates serious problems of market failure. As explained above, these are areas where research by private firms is unlikely to be appropriable and where agreement among firms is often problematical. In addition, the technological requirements for developing the AMRF are based in metrology and standardization. The next two chapters describe the technology of Flexible Manufacturing Systems and its components, the industries which use and manufacture these technologies, and their productivity benefits. The fifth chapter describes in more detail NBS research in the AMRF and how this research will support private-sector development and diffusion of automated production technology.

3

FLEXIBLE MANUFACTURING SYSTEMS: THE TECHNOLOGY

This chapter describes the concept of Flexible Manufacturing Systems (FMS), its components, and the expected productivity benefits of these technologies. The first section begins with a brief description of FMS. Section Two describes each of the components: numerically controlled machine tools, robots, measurement and sensor devices, and the integration of the system. Section Three describes the actual and expected benefits of FMS and its components.

FLEXIBLE MANUFACTURING SYSTEMS

The recent decline in American productivity growth and the increased level of international competition faced by U.S. manufacturers have spurred a renewed interest in automated production technologies. Flexible Manufacturing Systems incorporate many of the individual automation concepts and technologies already in use in the United States and abroad into a single integrated system. FMS has been described as a "group of NC machines or other mechanized workstations interconnected by a materials-handling system and all controlled by a computer" (Groover, 1980, p. 564). FMS is designed to automate all of the major manufacturing functions carried out in a discrete-product manufacturing plant: processing, assembly, inspection, parts transport, and storage. Because all of these functions will be integrated into one consolidated system under complex computer control, this manufacturing concept is also referred to as Computer-Integrated Manufacturing Systems (CIMS) or Computer-Integrated Flexible Manufacturing (CIFM).

Automated production can be traced back to Henry Ford and the early manufacture of automobiles. Today mass production technology or "hard" automation is characterized by highly specialized production equipment such as that still employed in the automobile industry. This specialized equipment is typically dedicated to performing specific functions and achieves very low unit costs for very large quantities of output. In contrast, "batch" production is far more flexible but the unit costs are much higher. Small job shops in the metal-working sectors typically manufacture a wide variety of different parts in small lot sizes. In small batch production, equipment must be flexible enough to adapt to the manufacture of new and different parts. Since there are considerable costs involved in changing from one batch to another, the "price" of manufacturing flexibility with respect to product and design changes is increased unit costs.

To some extent, computer-integrated flexible manufacturing will capture the efficiency advantages of hard automation along with the flexibility of small batch production. This occurs because the costs of changing from one batch to another will be greatly reduced using CIFM. Design changes can be made far more efficiently using computer-aided design systems and the altered data can be automatically transmitted to computer-controlled NC machines and robots. Instead of labor intensive and expensive new set-ups required to produce new parts, many of these changes can be made by simply changing software. Thus, the cost penalty paid to achieve increased flexibility will be reduced, and to some extent the efficiency benefits of mass production and the flexibility of batch production can be simultaneously attained.

While there is no complete FMS facility now operating anywhere in the United States that carries out all of the manufacturing functions enumerated above, automated technology has been implemented for each of the individual functions. Numerically controlled machine tools are integral to American manufacturing, and in the last decade computers have been used to control a number of NC machines in real time. The use of robots is growing rapidly, particularly in the "metal-working" sector. The U.S. robot population is now estimated to exceed 5,000 (Carnegie-Mellon University, 1981, p. 4). Materials-handling systems operating between workstations are as old as Detroit automation. Measurement devices and sensors are now used in a number of industrial processes. These sensors can be as simple as a thermostat which, when temperature-activated, initiates a cooling process, or as complex as robot vision. Finally, both increasingly powerful and miniaturized and inexpensive computers are being used in the home, school, and individual workplaces. However, the integration of machine tools and robots armed with complex sensor and measurement devices, all of which are connected by an automated workpart-handling system and computer-based telecommunications, awaits further developments in technology. The next section describes the individual components of FMS in much greater detail, as well as the requirements for a complex computer system linking them together.

COMPONENTS OF FMS

NUMERICAL CONTROL

Numerically controlled machine tools lie at the heart of a Flexible Manufacturing System (FMS). Numerical control (NC) is a form of programmable automation in which the process (e.g., drilling, milling) is controlled by a program consisting of numbers, letters, and symbols. This program of instructions can be easily changed when the job performed by the machine tool is altered. This capability of changing programs yields great flexibility, as it is far easier to write a new part program than to make major changes in production equipment.

Numerical control may provide significant productivity gains compared to conventional machining, particularly when there is complex part geometry, for which close tolerances are required, and where parts are processed frequently in small lot sizes. Numerically controlled machine tools are capable of performing such diverse tasks as drilling, milling, turning, grinding, sheetmetal pressworking, spot welding, arc welding, riveting, assembly, drafting, inspection, and part handling. In part because numerical control is suitable for so many manufacturing functions, there has been a tremendous growth in NC in the metalworking industries over the last 25 years.

A numerical control system consists of a program of instructions, a controller unit, and a machine tool. The program of instructions, or "part program" is fed into a controller unit, which consists of the electronics and hardware that read and interpret the program and convert its instructions to mechanical actions of the machine tool. Initially, the program of instructions was prepared manually by a part programmer. However, computer-assisted part programming, in which instructions are written in a high-level language especially developed for NC, is being used to an increasing degree to prepare NC tapes.

In more recent years, the computer has been increasingly used to control the functions of one or more machine tool systems. Whereas with computer-assisted part programming, a digital computer is used simply to prepare a tape of instructions, with direct numerical control (DNC), the computer is used to control one machine tool directly, or to control a host of separate machine tools.

ROBOTS

The Robot Institute of America defines a robot as a "programmable, multifunction manipulator designed to move material, parts, tools or specialized devices through variable programmed motions for the performance of a variety of tasks." Like machine tools, industrial robots can be programmed to carry out a sequence of precise mechanical motions repetitively until programmed to respond to an alternate set of instructions. Robots are particularly useful where the task performed is dangerous, boring, or difficult for humans. Thus, work undertaken in hazardous environments, tasks that are very repetitive, or jobs in which heavy objects must be lifted are ideally suited to robot performance. In addition, robots can be used to lower costs and improve the quality and consistency of products produced. Robots in use today perform simple repetitive tasks such as paint spraying, welding, machine loading and unloading, and very simple mechanical assembly.

Robots, like the more familiar variety of machine tools, can be computer-controlled. Indeed, the more complex robots may use small computers, which allow these robots to process input commands together with sensory input information from their environments. Recent research in robotics emphasizes the development of sensory capabilities such as touch and vision. These sensors in turn require the use of powerful computer hardware and software, capable of recognizing images, comparing them to various images stored in memory, and reacting accordingly in real time.

MEASUREMENT AND SENSORS

An integral part of a Flexible Manufacturing System comprises measurement and sensoring devices of various sorts. These may be stand-alone systems, such as coordinate measuring machines, or sensor devices incorporated into machine tools or robots. Vision systems or devices which monitor tool wear can be incorporated into robot systems or machining centers, respectively.*

Coordinate measuring machines (CMMs) are machine tools that measure, calculate, and record the dimensions of precision-machined parts. The more sophisticated CMMs are directly computer-controlled, that is, the precise database that accurately describes the part to be measured and the algorithms to measure the requisite dimensions are stored within the computer memory. When the program is run, no manual assistance is necessary; the computer itself directs a touch trigger probe or other device to measure the correct dimensions. Computer algorithms are also used to calculate certain dimensions. For example, the computer will automatically compute the radius and center coordinates of a circle when given three or more coordinates along its circumference. Coordinate measuring machines are being used today in the manufacturing sector to measure precision-machined parts. It is anticipated that CMMs will eventually be incorporated into a Flexible Manufacturing System. Here CMMs will be connected by an automated transfer system to the final workstation which machines the parts to be inspected. Although there is an increasing trend toward in-process measurement, it is likely that the first generation of computer-integrated Flexible Manufacturing Systems will rely in part on measuring the dimensions of precision-machined parts after they are produced.

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*It should be noted that these sensor systems may require the use of a powerful computer and complex software to achieve their stated purpose. This is most clear in the case of a vision system, where a computer is necessary both to recognize an image and to react to it according to a programmed set of instructions. Indeed, this type of feedback loop, requiring both computer hardware and software, is necessary to utilize almost any sophisticated sensor device.

In an automated, unmanned environment, measurement and sensor systems are essential to the operation of the whole system. Complex sensor systems can serve at least three functions: they can cut costs, increase the accuracy of machining, and eliminate the need for most human intervention. The latter two functions, increased accuracy and reductions in requirements of human labor, may in turn lead to further cost reductions. Robot sensory apparatus, such as touch and vision, can eliminate the need for, and thus the costs of, precise fixturing of parts. Likewise, machine tool sensors can cut costs by allowing optimization of cutting speed in response to feedback concerning cutting force. Also, the unnecessary costs of drill wear and breakage can be eliminated by the proper use of sensors that detect these "pathological" conditions.

Secondly, the accuracy of cutting machinery can be vastly improved by the combination of sensor devices and the appropriate software correction routines. For example, a drill may drift a tiny fraction of an inch in response to changes in temperature. If the relationship between temperature and the magnitude and direction of drift can be mapped out, and if sensors can measure temperature, the appropriate software correction routines can improve the accuracy of machining.

Finally, sensors may eliminate the need for frequent human intervention -- an essential condition for an automated environment. Tool breakage may require the halting of an entire assembly line while the damage is repaired. If tool wear or breakage is detected in advance and the tool changed automatically, human intervention (as well as the cost of temporarily shutting down operations) is eliminated.

COMPUTER INTEGRATION

Thus far, we have described several components of the hardware that are integral to Flexible Manufacturing Systems, numerically controlled machining tools and robots being the most prominent. Measurement and sensor devices will be incorporated into these pieces of hardware to cut costs, improve quality and accuracy, and facilitate the operation of FMS without humans. Automated transfer systems will also be required to link separate workstations physically, in order to facilitate the transfer and storage of raw materials, parts in process, finished products, and tools and fixtures. However, the computer software links, which integrate individual components into workstations and multiple workstations into flexible cells, are perhaps what differentiates the factory of today from the factory of tomorrow.

One or more computers will play a role in the control or operation of the separate elements of a Flexible Manufacturing System. For example, computers can be used to control the operations of numerically controlled machine tools directly and to assist in part-programming. Intelligent robots must contain microprocessors to interpret sensory information and redirect the robot's motions accordingly. Indeed, the use of any sensory information, such as measurements of tool force, requires a processing mechanism to evaluate inputs and make appropriate responses.

The computer requirements of an integrated system are far more complex than those required for the sum of the individual components. The computer handles all routing and scheduling plans, including the order of operation for all workstations. When one or more workstations are "busy," the requisite software will reroute the part if there is sufficient redundancy in the system. One or more computers must store precise part dimensions for all machined parts, including all dimensions of each part from the raw materials stage through the final product stage. The computer's database must also hold the dynamic information on the status of every part, tool, robot, and computer program at every point in time. Each component of the Flexible Manufacturing System requires immediate access to the information in this database in order to carry out its required functions.

The integration of these individual components into a Flexible Manufacturing System requires a very complex control system. A classic response to controlling a host of sensory interactive machines and robots, which in turn must interact with each other, is the establishment of a hierarchical control structure. Major goals or tasks are selected at the highest level of the hierarchy and commands are issued to the next level. Each level in the hierarchy decomposes its commands into appropriate subtasks and in turn passes on these commands to the next level of the hierarchy. The same procedure is repeated at all levels of the control hierarchy until a primitive sequence of commands is issued at the bottom level. These tasks can be executed with simple actions. The complex system of sensors and sensory processing algorithms facilitates the ability of each machine and system of machines to process their commands in the context of real-time environmental conditions. Thus, at every point in time, each control level must sample its commands, its sensory input data, together with its internal state, process these data, and issue output in the form of commands to the next level of the hierarchy. This structure, while exceedingly complex, transforms an unmanageable problem into a hierarchy of manageable tasks.

A final component in a computer-integrated Flexible Manufacturing System (implicitly assumed in the above discussion) is that involving interfaces between machines and indeed between parts of the same machine. As an example of the first, machine tools and robots must be able to "talk" to each other. As an example of the second, there may be a hierarchical structure that governs the behavior of a single robot. The high level, or machine-independent levels, of the hierarchy must be able to communicate with the low level, or machine-dependent levels.

EXPECTED BENEFITS OF FMS

Flexible Manufacturing Systems are expected to yield immense benefits in terms of reduced manufacturing costs, greater degrees of capacity utilization, higher-quality products, reduced lead times, safer workplaces, and greater flexibility. The cost reduction benefits of large-scale mass production and the flexibility of small job shops will be simultaneously achieved in an environment conducive to innovation. Some of these benefits of computer-integrated flexible manufacturing are or can be realized by usage of the separate components in today's manufacturing environment. For example, robots can be retrofitted in today's plants. However, other benefits of flexible manufacturing can only be realized when the entire system is integrated. The following paragraphs describe some of the benefits, actual and expected, of both existing components of FMS and of the entire integrated system.

NUMERICAL CONTROL

Unlike robots, numerical control has been in use for several decades in the United States. NC offers substantial benefits compared to conventional machining. First, numerical control increases the capacity utilization rate of machines. This is accomplished by decreasing the nonproductive time taken by setups, and reduces workpiece handling time along with the time taken to make tool changes. This increased capacity utilization rate serves to lower the average cost of machine operation. Further, since jobs can be set up more quickly, manufacturing lead time may be reduced. Second, NC reduces the cost of fixturing, since positioning can be done by the NC tape rather than the fixture or jig. Third, manufacturing flexibility is increased with NC. NC can adapt better to changes in scheduling and jobs than can conventional machining. Also, engineering design changes can be made more quickly and with less cost. Rather than altering complex fixtures, NC tapes can be modified instead. Finally, improved accuracy and reduced error is possible with NC. This is particularly true when parts are complicated and errors are common.

Within the last decade, numerically controlled machine tools have been directly controlled by a computer in real time. One computer can be used to control more than 100 NC machines simultaneously. This system eliminates the tape and tape reader required in more traditional NC systems, and is therefore more reliable. Greater computational capability is possible for functions such as circular interpolation. Thus, the accuracy of machining can be improved. Finally, one computer can control many machines.

ROBOTS

Robots currently perform many of the very repetitive tasks in a manufacturing environment that would otherwise be performed by humans. In a recent survey, when firms were asked the reasons why they had decided to purchase robots, the overwhelming response was the reduction in overall labor costs. Other reasons included the elimination of dangerous jobs, an increased output rate, improved product quality, and increased product flexibility (Carnegie-Mellon, 1981, p. 48).

Tasks currently performed by robots include welding, loading and unloading, paint spraying, and simple inspection. Robots are particularly attractive in hazardous workplace environments, or where the tasks to be performed are exceedingly repetitive and boring. Many of the cost advantages of robots stem from their ability to work three shifts a day, seven days a week. Additional benefits stem from their inherent flexibility. Tasks can be altered easily, simply by changing the software in the computer directing the robot's behavior. Finally, the quality and consistency of products produced by robots may be higher than corresponding products produced by human workers.

The scope and complexity of tasks that robots are capable of performing are expected to increase dramatically when their sensory apparatus is acquired or improved. That is, when robots are able to "see" or experience the sensation of touch, they will be able to react to much more complex environmental conditions without human intervention. The additional benefits attributable to robot sensory processing mechanisms are discussed below under the heading of sensors.

COORDINATE MEASURING MACHINES

Like robots, coordinate measuring machines can generate productivity benefits when used alone or when incorporated into a Flexible Manufacturing System.* Particularly when computer-controlled and computer-assisted, CMMs both increase the accuracy of measurement and greatly reduce the time taken to measure precision-machined parts. Time reductions reduce cost for two reasons. First, the time taken to do first-part inspections, when the machine tool is typically shut down, is drastically reduced, thus increasing the capacity utilization rate of machine tools. Second, inspection times of finished parts are greatly reduced and save the costs not only of the skilled (and often scarce) laborer, but also of special gauges. In addition, accuracy is likely to increase, and the improvement in measurement time may lead to an overall speed-up in the production process.

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*As indicated above, there has been a tendency toward in-process as opposed to post-process measurement. Although CMMs measure parts after they are manufactured, they are expected to be part of an automated factory in the near future.

A less recognized but very important byproduct of measurement accuracy is the increased tolerance allowed in the manufacturing process. For example, suppose that a part must be machined to within 1/1000 inch. If measurement is accurate only to 5/10,000 inch, parts must be rejected that vary by more than 5/10,000 inch in either direction from their proper size. If, on the other hand, measurement were accurate to 1/10,000 inch, parts could be accepted that varied as much as 9/10,000 of an inch from their intended dimensions. Thus, increased measurement precision can greatly increase the proportion of parts machined within an acceptable level of tolerance, and thus decrease the average costs of machining precision parts.

The decrease in measurement time may or may not increase the proportion of parts inspected. If the additional time is utilized by inspecting a higher proportion of parts, then the average quality will increase. On the other hand, if the proportion of parts inspected remains the same, the average quality will remain approximately constant, but the total of manufacturing plus inspection time will have been reduced.

SENSOR SYSTEMS

While individual components of Flexible Manufacturing Systems (such as robots and machine tools) can yield substantial productivity benefits without elaborate sensor feedback systems, the addition of sensor devices may also prove to be productive investments and is likely to be essential to sustained productivity advances in the future.

First, in order to operate in an automated environment, all machines must be equipped with sensor devices to measure their performance. These devices, together with the requisite software for sensory processing and appropriate correction, will to some extent eliminate the need for human monitoring and, thus, the costs of such monitoring. Further, to the extent that sensors can compensate for irregularities in the work environment, they may serve to increase the accuracy of machine operations.

Second, sensor devices can greatly reduce some of the costs associated with machining. For example, if a device is capable of detecting drill breakage before it occurs, the unnecessary costs incurred in shutting down a production line may be eliminated. The avoidance of breakage may also save the costs of ruining expensive subassemblies destroyed by a broken drill.

Third, a closely related benefit of the use of sensor devices in machining is the use of adaptive control on a continuous basis to optimize machining. Ideally, one wants to maximize the speed of machining subject to limits on the wear and tear of the tool. Cutting will typically occur on materials with uneven hardness or strength so that the cutting tool may encounter more or less resistance, and, in fact, it may move through air gaps from time to time. Thus, the optimal speed of a cutting tool may vary enormously from second to second. If sensors can detect cutting force, for example, the cutting speed can be adapted in process to optimize the cutting process.

Finally, sensor devices may make possible new uses of machines. A classic example is robot vision. Robots without vision can easily perform repetitive tasks such as paint spraying and spot welding. The objects upon which they perform these tasks, the bodies and joints of cars, for example, must be precisely located in space, time after time. However, there are many more complex robot tasks for which vision or other sensory capabilities is essential. These consist in part of tasks for which the work environment is irregular and precise fixturing is either impossible or prohibitively expensive. Assembly is a good example. Other robot tasks, such as inspection, require sensory feedback because a decisionmaking capability is necessary. Thus, the addition of sensory capabilities to robots would facilitate their use in assembly and inspection.

It should be mentioned that the use of any sensor device involves monitoring or measuring some environmental condition. However, in order for the monitoring to be useful, the information must be processed and compared to some set of expectations, and the appropriate decision must be made and communicated to the machine tool or robot. This process requires that the sensors be supplemented with microprocessor assistance and the appropriate software. The addition of computer control can greatly increase the versatility of machines or reduce the costs of performing old tasks. Thus, when machine tools are equipped with sensors and controlled by computers, adaptive control is possible. When robots acquire sensory devices they become "intelligent robots" capable of reacting to their environments and carrying out assembly and inspection. When CMMs are equipped with touch trigger probes, which automatically record contact with the surface of a machined part, automatic measurement is possible.

COMPUTER INTEGRATION

In addition to the productivity benefits realized when sophisticated sensor devices use computer hardware and software to assist robots and machine tools in reacting to their environments, the computer can be used to integrate individual components into workstations, and workstations into manufacturing cells, thereby attaining additional productivity benefits. The benefits realized by computer-integrated Flexible Manufacturing Systems are expected to exceed the sum of the benefits realized by its individual components.

First, computer-integrated flexible manufacturing is expected to increase dramatically the capacity utilization rate of metalworking machines, alleviating inefficiencies in the organization of workstations and saving time taken for tool changes, and the loading and unloading of parts. However, the most important reasons for the low utilization of cutting tools in metalworking sectors are incomplete use of the second and third shifts, holidays and vacations, and plant shutdowns for holidays, strikes, or other reasons. For low-volume plants, this "unproductive" cutting time accounts for more than three-quarters of potential capacity, and for medium-volume plants, more than two-thirds. Even for high-volume plants, productive cutting time lost to plant shutdowns is estimated to be 27 percent (Lawrence Livermore Laboratory, 1980). While metalcutting machinery appears to have the worst utilization rates, metalforming tools and welding tools also have very low capacity utilization rates. These are estimated to be 12 percent, 15 percent, and 22 percent for cutting, forming, and welding tools, respectively* (Ayres and Miller, 1981, p. 30). The computer integration of robots and machine tools could dramatically increase the utilization of capital equipment in the manufacturing sector.

Second, a closely related benefit of computer-integrated manufacturing systems is expected to be a large reduction in inventory costs. The Machine Tool Task Force has estimated that 95 percent of the time a workpiece is in a factory, it is in transit or storage (Ayres and Miller, p. 29). Computer-integrated flexible manufacturing can be expected to reduce idle time by improvements in scheduling efficiency and by increasing the capacity utilization of machine tools, particularly the addition of second and third shifts. Ayres and Miller report inventory-to-sales ratios in 10 selected steel products ranging from 9 percent to 24 percent with an average of 16 percent. They indicate that a 90 percent reduction in workpiece transit time is possible in several capital goods industries, including aerospace and machine tool producers (1981, p. 32). Even with only a 50 percent reduction in workpiece transit time, assuming a 15 percent opportunity cost of working capital, firms could immediately and permanently increase their rate of return on sales by more than 1 percent.

Third, reductions in the requirements for human labor, realized first when NC and robots were introduced, are expected to occur again when computer-integrated flexible manufacturing is implemented. This is particularly true for longer production runs, when human supervision is likely to be unnecessary.

Fourth, the flexibility of the workplace is likely to be increased when flexible systems are introduced. Thus, machines or robots can easily and instantaneously call on different software routines to manufacture different parts. Some of the benefits of flexibility have already been described above; for example, capacity utilization is increased. Further, producers can respond more quickly to changes in customer demand. In addition, flexibility lessens or eliminates the possibility of premature obsolescence of capital equipment. In contrast, the costs of the inflexibility of more conventional mass production technologies is well illustrated by the experience of Ford Motor Company. In order to convert one plant from the manufacture of 8-cylinder to 6-cylinder engines, complete retooling was necessary (Ayres and Miller, 1981, p. 14).

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*These estimates are based on a theoretical maximum of 20 hours per day, 7 days per week.

A more subtle benefit of flexible systems is that they may encourage innovation. Mass production techniques are only compatible with relatively standardized products. Once mass production facilities are in operation, the mere existence of capital equipment may act as a deterrent to innovation (Abernathy, 1976).

Finally, computer-integrated flexible manufacturing is likely to yield even greater benefits when the design and production stages of the manufacturing process are linked. Computer-aided design systems (CADs) facilitate the engineering, design, and drafting stages of product development by capturing and depicting the geometric properties of an object on a cathode ray tube, while precise dimensions are first recorded and later altered in the computer memory. Modifications in part design can be accomplished very efficiently, since redrafting is made unnecessary by the existence of computer memory and hard copy output capabilities. When CAD systems are linked to computer-aided manufacturing (CAM) systems, further benefits are realized, because the precise database from which a part is manufactured is already stored in computer memory. Thus, the ability to transfer electronically the design data into the manufacturing process greatly reduces transfer costs and reduces the costs of correcting errors.

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FLEXIBLE MANUFACTURING SYSTEMS: THE INDUSTRY

CURRENT AND FUTURE INDUSTRY TRENDS

Computer-integrated Flexible Manufacturing Systems do not yet exist in the manufacturing sector. However, several crucial elements of the technology have been operating for a decade or more. This section first reviews the current uses of various components of computer-integrated Flexible Manufacturing Systems, such as machine tools and robots. Since both the development and diffusion of these technologies depends, in part, on the structure of the industry, the robot and machine tool industries are also discussed. Finally, current and expected future trends in technology are discussed.

MACHINE TOOL INDUSTRY

Machine tools are power-driven machines that are used to cut, form, or shape metal. For our purpose, which is to describe the industrial underpinnings of flexible automation, the primary focus will be on SIC 3541, metalcutting machine tools, and SIC 3542, metalforming machine tools. The machine tool industry is relatively small -- shipments of machine tools total only about $5 billion per year, or roughly two tenths of one percent of the GNP (NMBTA, 1981). However, this small figure hides the extent to which machine tools provide the critical metalworking tools for nearly all U.S. manufacturing establishments. Most manufactured goods are made with machine tools or are made on machines built by machine tools. Hence the productivity of machine tools affects productivity in the entire manufacturing sector of the economy. Further, numerically controlled machine tools are the most important building block of Flexible Manufacturing Systems.

Since most of the new technology that makes machine tools more productive is embodied in capital equipment, it is instructive to examine the age distribution of the American machine tool population. Sixty-nine percent of machine tools in use in the United States are more than 10 years old. This figure compares unfavorably with that for Japanese machine tools, only 39 percent of which exceed 10 years in use (Carnegie-Mellon, 1981, p. 9). Further, enormous changes have been made in the technology of machine tools in the past several decades, beginning with numerical control in the 1950s. In the 1960s, Direct Numerical Control (DNC) was developed, whereby a group of NC machines could time-share a central computer, thus avoiding cumbersome NC tapes. Finally, as inexpensive minicomputers appeared on the market, it became possible to dedicate an entire computer to a single machine.

Machine tools are perceived both as a mature, technologically stagnant industry characterized by low-growth potential and also, paradoxically, as a dynamic, changing industry which will form the necessary foundation for highly sophisticated computer-integrated manufacturing technologies. These contradictory perceptions can easily be explained by examining the market structure and technological conditions that characterize the industry.

The U.S. machine tool industry is unconcentrated and fragmented. Both the metalcutting and metalforming machine tool sectors are populated with a few large establishments and hundreds of small producers. According to the most recent Census of Manufactures (U.S. Department of Commerce, 1977), the industries represented by SIC codes 3541 and 3542 have 4-firm concentration ratios of about 20 percent and 20-firm ratios of only 50 percent. Further, about two thirds of the firms in each of these classifications have fewer than 20 employees.

The machine tool industry has been described as tradition bound and fragmented. Most of the machine tool builders are small operations serving specialized customers. Many are owned by people who are craftsmen and do not employ engineers or technically trained people. That neither the size, fragmentation nor tradition of the industry is conducive to innovation is reflected in 1981 data indicating that the R&D sales ratios in the Machinery (machine tools, industrial, mining) sector averages only 1.9 percent. This compares unfavorably with 6 to 7 percent in the high-tech areas of computers, peripherals and services, and semiconductors (Business Week, 1982, p. 72).

As may be expected from this description of the machine tool industry, the major changes in machine tool technology have been effected more by influences outside the industry, that is, by supplying and using industries, than by the machine tool industry itself. The single largest change in machine tool technology in the last several decades has been Numerical Control (NC). Both NC and related technological developments were the product of rapid progress in computer and electronics technologies. Further, the development of NC was subsidized by the U.S. Air Force for application in the aerospace industry (Lawrence Livermore Laboratory, 1980, Vol. 1).

Using industries have been and continue to be a driving force in the changes of the machine tool industry. Two of the largest users of machine tools have been the automotive and aerospace industries, both of which have recently increased their requirements in terms of work-piece materials, an expanded mix of parts to be manufactured, and part accuracy. For example, automotive manufacturers are turning increasingly to aluminum alloys and plastics in order to reduce car weight. These material changes, in turn, require processing changes and modifications of machine tool design. Since aluminum can now be cut at much higher speeds, the problems of handling increased tool chatter, tool wear, and inadequate chip handling must be solved. Also, both the automotive and aerospace industries require multipurpose machinery to produce a greater variety of parts, greater part accuracy, and multiaxis machinery for the more complex parts. Thus, in addition to the application of computer and electronic technology, another "external" source -- large, economically powerful buying industries -- may be responsible for changes in machine tool technology (Lawrence Livermore Laboratory, Vol. 1, 1980).

Thus, the machine tool industry can probably be characterized as a small, unconcentrated, fragmented industry with a low level of research intensity. Major changes in technology have been due to changes in computer technology and the needs of large powerful buyers. However, in addition to large buyers, users span the range of the entire metalworking sector. The diffusion of numerical control overall has been quite slow. Numerical control even today represents only a small portion of machine tools in use, about 3 percent in units and 25 percent in value in 1980 (NMTBA, 1981). Three decades after numerical control was developed, its use is not widespread throughout the manufacturing sector. The apparently low penetration could be due to the fact that the productivity impacts of NC can only be realized by a small class of users of machine tools, or that potential buyers are poorly informed or capital constrained, or that the machine tool industry has tailored NC to only a few market segments. Whatever the reason for the low penetration of NC, this fact has implications for the ultimate productivity impacts of flexible automation, of which machine tool technology is a fundamental building block.

ROBOTS

Although the era of the flexible manufacturing cell has not yet arrived, there were more than 5,500 robots operating in American manufacturing plants in December 1981, up from 3,500 in June of 1980 (Carnegie-Mellon, 1981, p. 4). All or nearly all of the robots are being used in the "metalworking" sector (SIC codes 34 to 37). These sectors include fabricated metal, machinery (both electrical and non-electrical), electronic equipment, and transportation equipment, and comprise about 38 percent of American manufacturing employment. According to one estimate, as many as 55 percent of all robots now in operation are being used in the manufacture of motor vehicles and equipment (Carnegie-Mellon, 1981, p. 5). These robots are being used primarily for part transfer, spot welding, and spray painting. Although the use of robots for purposes of assembly is not now predominant, assembly is projected by General Motors to become the most common function performed by robots in 1990 (Carnegie-Mellon, 1981, p. 65).

Initial users of robots tended to be very large firms. However, subsequent users also included small and medium-sized firms. For example, whereas a recent survey indicated that pre-1976 users consisted only of firms employing more than 1,000 workers, the same survey revealed that the profile of prospective users was distinctly different. More than 50 percent of prospective users employed fewer than 1,000 workers, and more than one-third employed fewer than 500. Two prospective users reported that their firms employed fewer than 100 persons. Depending on economic factors encouraging or discouraging the addition of robots by firms of varying characteristics, the proliferation of robotics technology may not only improve overall manufacturing productivity, but also alter the competitive conditions within industries.

The robot industry is now a tiny industry, only a fraction of the size of the machine tool industry, but it is characterized by rapid growth, rapid change, and a relatively high degree of research intensity. Sales totaled about $100 million in 1980 and $150 million in 1981, and are expected to experience increases in the 30-50 percent per year range for the foreseeable future.* General Motors alone plans to increase robot use by a factor of 50 by 1990 (Carnegie-Mellon, 1981, p. 62). Future growth trends are expected to include the use of robots by greater numbers of firms, new uses for robots, and the eventual incorporation of robots into flexible manufacturing cells.

The domestic industry is currently dominated by two producers, Unimation and Cincinnati Milacron. Unimation, a specialized producer before its acquisition by Westinghouse in early 1983, is estimated to produce about 40 percent of total market sales. Cincinnati Milacron, one of the largest machine tool producers, accounts for another 30 percent of total robot sales. Although production is currently highly concentrated in these two and a handful of other firms, the very rapid growth of the market, and quickly developing technology, offer opportunities for new entry and expansion. Indeed, a number of very large firms -- General Electric, Westinghouse, Bendix, Texas Instruments, GM, and IBM -- have all recently entered or announced plans to enter the robot market. Further, dozens of smaller more specialized producers have entered the industry during the last year or so. Given the very early stage in the life cycle of the robot industry, as evidenced by its small scale, rapid growth, and dynamism, it would be instructive to examine more closely the technological conditions that underlie the production of robots.

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*Estimates from Bache, Halsey, Stuart Shields, cited in New York Times, March 4, 1982; Paine Webber Mitchell Hutchins, Exploratory Workshop on the Social Impacts of Robotics, Summary and Issues, Office of Technology Assessment, 1981; and Carnegie Mellon University, Impacts of Robotics on the Workforce and Workplace, June 1981.

Robots are said to have a dual technological ancestry, which has an effect both on the current state of the market and its future development. The first area from which robotic technology descended is that of industrial engineering automation technology; the second stems from computer science and the burgeoning field of artificial intelligence.

Most robots currently operating in the workplace are simply extensions of automated assembly-line technology. They have been designed to carry out a variety of simple repetitive operations such as spot welding, spray painting, and simple materials handling "pick and place" operations. These robots are usually designed and purchased to take the place of a human worker in an automated assembly-line type environment. The robot industry has been able to take advantage of the same technological advances as have influenced the development of machine tools. In particular, a numerically controlled robot is one that can perform a series of tasks according to instructions commanded by numerical data. It has the same control mode as an NC machine tool.

In contrast to the relatively "low-tech" robots which comprise the vast majority of working robots in both the United States and worldwide, intelligent robots are quickly evolving from the developing technologies of computer software and hardware and from artificial intelligence. These robots may soon possess visual and tactile senses, be able to react to their physical environments, and even understand spoken language. Clearly, the range of uses of intelligent robots greatly exceeds the fixed automation environment of current robots and perhaps exceeds the current human imagination. An important point is that intelligent robots, with sophisticated sensory capabilities, can be designed to perform a variety of more complex tasks in small batch manufacturing. These manufacturing environments in which robots will play a crucial role, are ones in which entire systems are designed to produce a variety of parts in medium to small lot sizes with minimum downtime between production runs. This stands in contrast to most current robots that replace human workers in existing assembly-line type environments.

Although the numerical control and simpler robots form the vast majority of the robot population, they are very far from the point of saturation or market penetration. As indicated above, the robot population is expected to grow at about 40 percent per year for at least the next decade. There have even been some indications that in many cases robots are overdesigned for their current uses. A firm may use a programmable robot for the same task repeatedly when a fixed sequence manipulator would have performed the same task. On the other hand, a vast new variety of uses opens up for robots with intelligence. Many of these uses will be in the context of a computer-integrated flexible manufacturing environment where robots perform valuable materials handling and inspection roles. In contrast to the simpler robots that perform functions in the current environment of fixed automation, intelligent robots are more likely to work in flexible cells designed to operate without humans. Thus, the usefulness of intelligent robot technology may be dependent on the development of flexible systems and the computer control systems and interfaces which control and connect these systems.

The technological ancestry of the robot industry helps to provide a basis from which we can understand the current patterns of entry and growth in the market. Our research indicates that existing robot firms have entered the market from four very different starting points which reflect both the technological and financial requirements for success in robot production. One point of entry has been the machine tool industry. Cincinnati Milacron, for example, is currently one of the largest producers of both machine tools and robots. As indicated above, technological developments are proceeding in parallel in both industries. More "intelligence" is being incorporated into both machine tools and robots as both acquire the ability to sense their environment and react to it in real time with the aid of one or more computers. Also, robots and machine tools are likely to work together in the context of a Flexible Manufacturing System. Thus, to the extent that there is a software or hardware interface problem, firms producing both machine tools and robots will have an advantage.

A second group of robot producers consists of the well-established specialized firms, such as Unimation, at least before its acquisition by Westinghouse. A third group consists of the recent entrants that are large manufacturing firms, particularly electronic and computer equipment manufacturers. These firms have massive research budgets to devote to robots and some, such as General Electric and Westinghouse, are making larger efforts to build productivity centers or automated factories. Others such as Texas Instruments have developed or are developing robots primarily for internal usage. Texas Instruments as well as IBM, GE, and Westinghouse will be able to test their robots under actual production conditions in-house. This is the pattern typically followed by Japanese and European producers, particularly the automakers such as Toyota, Mitsubishi Motors, Fiat, Volkswagen, and Renault. Thus, it appears that a knowledge of the factory environment may be important to the successful production of robots.

A fourth group of entrants into the robot market consists of small entrepreneurial firms that develop new robot products to fill some niche in the market. It is unclear at this time whether or to what extent the large new entrants with a backlog of experience in either manufacturing production or electronics and computers will greatly increase their market representation at the expense of smaller firms. Several considerations will be important in this determination, with pricing, progress toward system integration, and user acceptance being among the most important.

The pricing over time of intelligent robots as compared to simpler variable sequence manipulators and playback robots may be an important factor in the development of the robotics market. Currently about 30 percent of the cost of a typical robot is due to electronics and software. This percentage is even higher for the most sophisticated robots (Lustgarten, 1981). If electronic and software prices continue to fall over time (relative to the hardware comprising the rest of the robot), sophisticated robots should gain a cost advantage over their less sophisticated counterparts. This phenomenon may favor larger producers, such as General Electric, which are investing large research funds in robotic assembly, robot vision, robot controllers, and new VSLI micro-circuit technology.

A second important factor in the development of the robotics industry is the extent to which robots will become an integral part of Computer Integrated Flexible Manufacturing Systems and the ultimate acceptance of CIFMs. The development and widespread diffusion of CIFM technology is itself dependent on the development of control systems and interface standards. Widespread use of this systems technology may tend to favor the larger robot producers who also manufacture computer-controlled machine tools or who supply turnkey systems. On the other hand, when and if standards are developed to interface robots and other elements of flexible automation, small specialized manufacturers of robots may not face significant disadvantages.* Further, a continual expansion in the user market for the current generation of robots would favor the smaller and less research-intensive firms who produce standardized robots to do paint spraying, spot welding, and other functions which do not require intelligence.

Finally, the ultimate acceptance by users of new flexible automation technologies may strongly influence the development of the market structure for robots. In particular there is likely to be far more resistance to robotics in uses where humans are directly replaced on the assembly lines than where new factories are designed to accommodate robots. This fact may also favor producers of CIFM systems and/or robots that are compatible with these systems.

FLEXIBLE MANUFACTURING SYSTEMS

There are no computer-integrated Flexible Manufacturing Systems of the type being built by NBS currently operating in the United States. However, less sophisticated versions of Flexible Manufacturing Systems (FMS) are currently being used in about a dozen establishments in the United States and even more abroad. According to one definition an FMS is a "computer-controlled configuration of semi-independent work stations and a material handling system designed to efficiently manufacture more than one part number at low to medium volumes." Three essential features of an FMS are:

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*A small, specialized manufacturer of robots could still face significant disadvantages relative to larger rivals if there are economies of scale in either research or production.

- Standard numerically controlled machine tools;
- A conveyance network to move parts and perhaps tools between machines and fixturing stations; and
- An overall control system that coordinates the machine tools, the parts-moving elements, and the workpieces.

As indicated, these systems are now being used in several establishments in the United States and more extensively abroad. These firms include AVCO, International Harvester, Caterpillar, John Deere, and Allis-Chalmers. Plans have been made to install and operate several more in the near future. These FMS consist of a number of numerically controlled machining centers, connected by a materials handling system and linked and directed by a central computer. They are extremely flexible in that a multiplicity of different parts can be manufactured with quick changes in software. Unlike the AMRF planned at NBS, no robots are being used in the current generation of FMS. Rather, the materials handling function is typically served by carts or roller conveyers.

The current generation of FMS operating on the manufacturing floor is not unmanned. Although there has been considerable reduction in the usage and cost of labor, people are still required to maintain operations. These typically include one foreman, one or more leaders to feed the line and, at least in the initial stages of operation, one machinist to tend up to six machining centers. In contrast, the planned NBS system will be unmanned.

Potential productivity impacts include large reductions in labor requirements and costs, and high capital equipment utilization. This high utilization rate is due both to reduced set-up times for new parts and improved scheduling, since the computer will schedule every part to a machine as soon as it is free. The high utilization in turn facilitates increased output rates, reduced in-process inventories, and reduced lead times. Flexibility is introduced; therefore, different products can be quickly produced as market demands change or new engineering designs are introduced.

The hardware portion of FMS is very well developed technologically. Further FMS improvements must come in the software and in the integration of both software and hardware. Indeed, the realization of high profitability may depend on the maintenance of a high capacity utilization rate for FMS. This, in turn, requires the solution to highly complex scheduling and routing problems, and therefore improvements in software to handle a greater variety of contingencies. Improved scheduling and routing algorithms are not only necessary during normal operating periods, but also essential when one or more machines fail. If sufficient redundancies are built into the system, parts can be rerouted through the materials handling system to maintain throughput.

Perhaps half of the total value of FMS currently being sold is in the NC machining centers. Other essential components include computers, programmable controllers, a materials handling system, and fixtures and tools. Perhaps due to the high proportion of value accounted for by NC machines, all current manufacturers of FMS are machine tool producers. Kearney and Trecker appears to be the leading producer. Others include Cincinnati Milacron, White Sundstrand, and Giddings and Lewis. These firms typically buy one or more components from other firms and develop the software themselves. Future entry may well occur from the machine tool industry. Additional entry is likely to occur by firms such as Westinghouse and General Electric which are producers of robots and are investing large research sums in productivity and flexible automation.

The FMS currently being manufactured are relatively expensive. The cost of each machining center (including the pro-rated cost of the computer and other essential elements) ranges from 1/2 to 1 million dollars. Systems in existence and planned may include anywhere from 4 to 16 machining centers. Thus, a typical price for a sophisticated FMS may be in the $10 million range. Because a high proportion of this cost is in the machining centers, where the technology is "mature," one would not expect this cost to fall appreciably in the future.

Both the cost of FMS and their characteristics will help to determine the potential user population. FMS are likely to be most productive where parts to be manufactured are very complex, and are made in relatively small batches. Thus, the defense industries (e.g., aircraft, tanks) as well as tractors and automobiles are potential candidates for FMS. FMS are likely to have fewer ultimate uses than robots, due to the latter's greater flexibility.

Robots can be used not only as an integral part of an FMS, but also as stand-alone entities in the context of mass-production environments. The cost differences between a computer-integrated Flexible Manufacturing System and a single robot are likely to exacerbate this tendency.

The current generation of FMS is partly manufactured, assembled, and integrated by single firms. Since all the software is typically developed by these firms, no standardization problem currently exists. However, there are two potential future areas where standards may become an important issue. First, if current or future users wish to expand their FMS to include NC machines from other vendors, standards for interfaces will be necessary. Secondly, in order for modular systems to be sold, where small manufacturers can purchase one or a few machines at a time to suit their financial constraints and corporate strategies, interface standards will be necessary. Thus, both the development of CIFM technology and its ultimate diffusion are likely to depend on the timing and quality of interface standards. Further, the development of interface standards may be crucial to the market structure in the "CIFM" or related industries. Entry is likely to be far easier and an unconcentrated market is more likely to develop if firms manufacturing individual components can enter with the knowledge that their products are compatible with the rest of the system. Also, since diffusion may be a function of the size of the investment required, faster diffusion may result from a modular system where components may be separately purchased.

FUTURE TRENDS IN TECHNOLOGY

Future advances in the technology of robotics can be expected in several related areas. First, robots will likely incorporate sensor devices. These devices can be contact sensors (e.g., touch, force, torque) or noncontact sensors (e.g., vision, ultrasound). Second, robots will increasingly be controlled by computers. Third, there will be an increasing trend toward a systems approach. That is, robots will work in tandem with machine tools and a materials handling system. Finally, there will be an increasing proliferation of specialized languages for the control of robots.*

Similar trends are apparent in the development of the technology of machine tools. The Machine Tool Task Force found that the single largest force encouraging past, present, and future technical change in machine tool technology is rapid progress in computer technology and associated developments in electronics (Lawrence Livermore Laboratory, 1980, Vol. 1, p. 4). Advances in solid-state electronics increasing the capabilities of computers and lowering their price have led to two significant extensions of numerical control technology, direct numerical control (DNC), and computer numerical control (CNC).

The Task Force indicated that there are two external sources of influence currently driving machine tool technology. The first is greater capabilities and lower prices of microprocessors. The second is demand on the part of machine tool users for machines capable of cutting and forming an increased variety of materials, and creating more complex part geometries. Whereas aerospace machining was dominated by aluminum alloys and automotive machining by iron and steel, materials diversification is occurring very rapidly in both industries. The aerospace industry is increasingly turning to titanium and composites, while aluminum alloys and even plastics are being used in the manufacture of automobiles to reduce car weight. According to the Machine Tool Task Force, these changes will require significant modification of machine tool design. For example, aluminum can now be cut at much higher speeds; however, increased tool wear is a byproduct. One possible solution to this problem would be to use more sophisticated sensor devices to detect and/or control the degree of tool wear.

The other need voiced by the users of machine tools is for machines capable of more complex part geometries, and capable of machining a larger variety of parts. These needs can be satisfied by greater dimensional accuracy and by greater flexibility.

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*Based on a conversation with a prominent research scientist at a robot systems company.

Thus, it appears that technological developments in both robotics and machine tools point in the same direction. First, both robots and machine tools are likely to make a much greater use of sensor devices. Both robots and machine tools may require sensors to obtain feedback about the environmental conditions in which they are operating. Robot vision facilitates picking up and placing metal parts and tools. Vision also facilitates robotic assembly and inspection. A sense of touch is required if a robot is to have the dual capabilities of picking up a delicate object without crushing it and a heavy object without dropping it. Machining centers require sensors to measure cutting force or horsepower in order to optimize cutting speed. Sensors could also be used to detect tool wear or breakage.

In order to process the output of sensor devices, the capabilities of a computer will be needed. Indeed, trends in the technologies of both robotics and machining point to a greater use of the computer, not only to process sensory input, but also to control the operations of the system. The greater flexibility required by machine tools and the flexibility made possible by robotics require the use of appropriate software to accommodate the cutting or manipulation of parts with varying geometric and material properties. Thus, a second important trend in the technology of robotics and machine tools is the increasing use of computer control. As the complexity of tasks and the requirements for processing interactive data in real time increase, the need for more complex control systems increases as well.

Third, there may be a more urgent need for interface standards. For example, standards are necessary between robot arms and robot grippers. Standards are also necessary between high-level robot-independent languages for controlling robots and low-level robot-dependent languages. Further, to the extent that robots and machine tools equipped with sensor devices are to be integrated in a computer-integrated flexible manufacturing cell, interface standards will be necessary between these modules (NBS, 1980).

5

THE AUTOMATED MANUFACTURING RESEARCH FACILITY AT NBS

For the last decade, NBS has been engaged in infratechnology research and generic technology research in many areas, including robotics and robot vision systems, coordinate measuring machines, and sensor systems. More recently, NBS has embarked on the design, procurement, and installation of a fully-automated manufacturing research facility (AMRF) in support of its measurement and standards responsibilities. This facility will eventually provide all the capabilities of a flexible manufacturing cell. NBS is purchasing the components of the system, such as robots, machine tools, and computers, from various vendors in the marketplace. AMRF will function as a "test bed" for developing "means and methods" of doing precise measurements needed by an integrated manufacturing system. This chapter first describes NBS's Automated Manufacturing Research Facility. Section Two describes how the changes taking place in the technology of Flexible Manufacturing Systems are appropriately supported by NBS research on measurement and standards in conjunction with the AMRF. Finally, Section Three indicates how NBS may have as much influence on the diffusion of Flexible Manufacturing Systems as it does on innovation.

AMRF

The AMRF is being developed to manufacture individual parts by chip-forming metal removal. It will consist of eight relatively self-contained workstations, including a horizontal machining station, a vertical machining station, as well as stations for turning, cleaning and deburring, and inspection. The materials handling system is used as a buffer to allow storage of raw materials, parts in process, tools, fixtures, and finished parts.

Each self-contained workstation will consist of a general-purpose machine tool in common use in the United States and an industrial robot. The purpose of the robot will be to transfer parts, tools, and fixtures to the machine tool from the materials handling system, fixture the part, and monitor the machining process. In order to grip and position a variety of parts precisely and to fixture the parts accurately, the robots will require considerable sensory (touch and vision) capabilities.

The control architecture of the AMRF is enormously complex. The hierarchical control system being developed allows each level of the hierarchy to take commands from above, monitor its internal state, accept sensory input from levels below, and take appropriate actions in terms of subcommands to lower levels of the hierarchy. There is a common memory "mail-drop" system which contains detailed information concerning the precise geometry of all parts, fixtures, and tools, and the precise activities currently being undertaken by all machines, robots, and computer programs. All modules communicate by transferring and obtaining data to and from the common memory.

NBS ROLE IN TECHNOLOGY

The recent trends in the technology of computer-integrated flexible manufacturing described in Chapter 4 as well as the technological advances required to integrate today's robots and machine tools into flexible systems, conform closely to NBS' traditional role in infratechnology and closely related generic technology research and its work in the AMRF. In order to operate in an automated factory environment, all machines must be equipped with sensors to monitor their performance and to react to or compensate for uncertainties in their environments. Research in sensors, such as vision or touch for robots, or sensors to measure force or toolwear on machine tools, can be characterized as generic technology research. Further, much of the research on sensor devices may require advanced measurement capabilities, thus encompassing infratechnology research as well. The generic technology research role is appropriate for NBS in this case because it is itself measurement intensive and is a necessary first step in developing the research competence. The use of intelligent robots in the AMRF to load and unload machines and fixture parts precisely will require these advanced sensory capabilities.

A second and related trend in the technology of computer-integrated flexible manufacturing is the increasing use of the computer to control the activities of robots, machine tools, the sensors to which they are attached, and materials handling equipment, all in real time. Much of NBS' work in the AMRF is focused on the development of hierarchical control systems. These control systems break into smaller, more manageable modules the enormously complex problem of integrating the activities of robots and machine tools into workstations and workstations into flexible cells by establishing a system of hierarchical control. Here each level accepts commands from a higher level and in turn issues subcommands to a lower level. These subcommands are issued at each level based on the processing in real time of commands, sensor data, and inputs concerning the external and internal environment. The principles and concepts related to the control of complex systems can be characterized as generic technology research because they represent basic scientific and technical knowledge from which proprietary applications can be drawn. Control systems can apply to the control of a simple robot as well as a more complex flexible manufacturing cell. In each case, the underlying research contributes relatively nonproprietary knowledge from which the entire manufacturing sector may eventually benefit. Because such knowledge will apply to several components, likely produced by different firms, compatibility of the proprietary components requires this common underlying generic technology. Thus, the development of control systems is likely to have attributes of a public good, making research by private firms unappropriable. Secondly, the demonstration that complex hierarchical control structures can be successfully used to control an entire flexible cell will increase the incentive of suppliers to undertake proprietary research activities in this area. Such demonstration effects will likely accelerate the growth of demand as well by reducing uncertainty with respect to performance characteristics and general engineering requirements.

The third and related requirement in the development of its AMRF facility is standardization. This clearly is within NBS' traditional role of facilitating the adoption of standards in support of industrial innovation and growth. There is now an articulated industry need for interface standards for robots. For example, standards are needed between the robot wrist and the robot gripper. (These are sometimes manufactured by different firms.) In addition, the need to facilitate communication between different components of flexible cells is expected to require additional interface standards in the future. Thus, not only will communication be required between the high-level languages developed to control all robots and the lower-level languages that are machine-dependent, but robots must communicate with the machine tools with which they work. While standardization would provide great societal benefits, no one or small group of firms has the requisite incentives to develop standards to govern communication between components of a computer-integrated Flexible Manufacturing System. The design and installation of an automated manufacturing research facility that incorporates robots and machine tools of different vendors requires the development of a communications interface between individual components. NBS is deliberately purchasing machine tools and robots from a variety of vendors. One of the goals of the automated manufacturing research facility is to develop a set of interface standards that demonstrates to the manufacturing community both that communication between modules is possible and that it can be accomplished without sacrificing proprietary interests.

We have identified the concept of a Computer-Integrated Flexible Manufacturing System, its components, and the contribution that Flexible Manufacturing Systems might make to overall productivity growth. We then identified three trends in the technology that are essential to the further development of CIFM systems. These are the increasing use of sensors, the increasing use of computer-based control systems, and the need for interface standards. All of these were seen to involve strong elements of infratechnology research and generic technology research that characterize NBS' traditional role and Congressional mandate. Indeed, the automated manufacturing research facility is being installed to provide the means by which to examine the issues of sensors, control systems, and interface standards.

NBS ROLE IN DIFFUSION

The NBS traditional role has been to support industrial innovation and growth through its work in metrology, standards, and related services to industry. The major changes currently taking place in technology of Flexible Manufacturing Systems lead logically to the NBS research centered around the AMRF. Perhaps more importantly, however, NBS work may serve to further the diffusion of automated production technololgy. This section describes briefly several ways in which NBS research may serve to speed the diffusion of automated production technologies. Subsequent chapters explore the literature on diffusion and its determinants in order to depict more precisely the ways in which NBS may facilitate the diffusion process.

MODULARITY

The AMRF is being designed to be a "modular system" typical of the Flexible Manufacturing Systems to be used in the discrete parts industry. The "discrete parts industry," according to NBS, embodies a collection of firms, 87 percent of which employ fewer than 50 persons. Considering the size of such establishments, it is necessary for using firms to be able to start by purchasing an NC machine, and successively add robots and machine tools as needed. The interface standards and the control architecture must be developed to accommodate this modularity. The advantages of modularity are as follows:

- Lower initial costs of installing a Flexible Manufacturing System;
- System growth can proceed along with the needs of the firm; and
- Compatibility with future machine and robot purchases is assured.

Given these advantages, more firms will be able to purchase FMSs. In addition, the modularity will widen the variety of vendors, whereas single systems may be too large and complex to be supplied by more than a handful of large firms; with interface standards, smaller firms can supply sensors, robots, or machine tools alone.

NBS AMRF WORKING FACILITY

The existence of the AMRF facility capable of manufacturing a diverse group of parts will reduce uncertainty concerning the capabilities of FMS. As we shall see in the remaining chapters, a substantial deterrent to the diffusion of a new technology is often lack of information or uncertainty concerning its benefits, implementation costs, and required changes in the roles of management and workers. The existence of the AMRF will:

- Lower uncertainty as to FMS technological capabilities. Interested parties will be able to observe the capabilities of the AMRF in manufacturing parts; and
- Lower uncertainty about engineering design requirements, including plant organization and utilization, amount and type of labor, and requirements for parts inventory management.

In short, the existence of the AMRF will substantially reduce the "fear of the unknown" that may influence managerial decisionmaking.

6

MARKET STRUCTURE, DIFFUSION, AND PRODUCTIVITY IMPACTS

The productivity impacts of a new technology depend on both the nature of the technical advance and the market structures of the supplying and using industries. Moreover, because productivity impacts are realized only as the new technology becomes diffused or adopted by more firms, and the pattern of diffusion depends importantly on the structures of the pertinent markets, characterization of the market structures and environmental conditions in which supplying and using firms operate is essential to an analysis and projection of productivity impacts. This characterization is also important for an assessment of how NBS research in the AMRF may facilitate the diffusion of technology. This chapter describes available economic research on the diffusion of innovation. The first section below will describe in more detail why an understanding of the market structure, technology, and environmental conditions under which firms and industries operate is crucial to the understanding of both the innovation and the diffusion processes and thus to any evaluation or projection of productivity impacts. The second section describes the major theoretical principles used to construct models of the speed of diffusion. The third section describes research results concerning the speed of diffusion and its determinants. The final section provides a critical assessment of the economic literature on diffusion.

INNOVATION AND DIFFUSION

Economists have long debated the question of the conditions that are most conducive to industrial innovation and economic growth. For the most part debate has focused on the ideal conditions of market structure in the supplying industries. Later, as economists realized that productivity increases can only be experienced as new technologies are diffused throughout industry, more attention has focused on the diffusion of these innovations in the using industries.

Early economists believed that perfect competition represented ideal conditions not only for the existence of static efficiency but also for the promotion of innovation. Small firms striving for maximum profits in a competitive marketplace would seek to stay ahead of their competitors in developing a cost-saving innovation. It was not until the era of Joseph Schumpeter that economists began to think seriously that monopoly, or at least some market power, might be a necessary condition for industrial innovation. Schumpeter argued that firms might invest in innovation activities in order to attain a monopoly. More importantly, he argued that a condition of market dominance might be necessary in order for firms to be able to take advantage of the fruits of their efforts, and therefore that firms possessing market power might have greater incentives to innovate.

A more modern perspective of innovation begins with the notion that firms investing to maximize profits in a dynamic, competitive, industrial environment must consider the likelihood and extent to which they can profit from the investments they make in innovative activities. Secondly, firms must also consider the extent to which they might be penalized for not engaging in innovative activity, when and if they are surpassed by their competitors. Third, firms must assess the underlying technological conditions of their industries as well as the economic environment in which they sell their products.

The first consideration mentioned above can be best understood in terms of appropriability. If firms do choose to innovate, their rewards will be a function of the extent to which they can profit from the sales of lower-cost products or new or improved products before imitation takes place. Logic would indicate that those firms without a serious threat of rapid imitation, that is oligopolists or monopolists, would thus face the greatest incentives to engage in innovative activity. This is the Schumpeterian idea. Ease of imitation depends not only on market structure but also upon whether the innovation is patented or can be protected as a trade secret.

In addition, regardless of the market structure of the innovating industry, the profitability derived from innovation will be greater the larger the size and rate of growth of the industry or industries using the new technology. In general, the more rapid the expected rate of diffusion of new technology and the faster the rate of growth of the using industries, the greater the expected profitability of innovation and thus the incentives to innovate.

Whereas the expectation of being able to appropriate the profits from innovation may be an important factor in encouraging innovation, the expectation that one's competitors would innovate first and thereby capture the bulk of a new or growing market may also provide competitive pressures to innovate. This line of thought would indicate that some degree of competition is necessary for providing the proper inducements to innovate.

Thus, the question of the ideal market structure for the promotion of rapid technical innovation becomes an empirical question. This question has been the subject of much speculation and a considerable degree of empirical testing over the last few decades. Most researchers have concluded that a moderate degree of concentration as well as moderate barriers to entry constitute a market structure particularly conducive to innovation (Kamien and Schwartz, 1975 and Scherer, 1980). This market structure configuration thus apparently provides both the incentives of competition as well as some protection from rapid imitation. Other factors such as the nature and size of the research required, the ease of imitation, and, perhaps most importantly, the degree of "technical opportunity" provided by underlying scientific discovery may be crucially important factors in determining the direction and speed of innovation.

DIFFUSION -- THEORETICAL PRINCIPLES

While rapid innovation is certainly a prerequisite to the overall increase in productivity, unless the improved products or processes introduced as a result of innovation are adopted by using firms (or consumers) productivity increases will not be experienced. Thus, the diffusion of innovation acquires a new sense of importance.

The diffusion of new technology usually involves the substitution of a superior technology for a less productive one or the addition of new technology to existing processes. As such, diffusion is inherently a dynamic process -- it involves the transition of productive activity from one state of equilibrium to another. Early efforts of economists to model the diffusion of innovation began with Griliches and Mansfield, who used the same methodology as had been used by epidemiologists to describe the spread of infectious disease (Griliches, 1957 and Mansfield, 1968). Mansfield postulated that the rate of imitation, that is the rate of adoption of new technology by non-users, is proportional to the number (or proportion) of current users of the technology. It was reasoned that both the knowledge concerning the new technology and the competitive pressure to adopt increased with the number of users and as the risks of adoption decreased. Thus:

$$\frac{\frac{dm}{dt}}{n-m} = \beta \cdot \frac{m}{n}$$

where m = the current population of users,

n = the population of potential users, and

β = the speed of diffusion parameter (to be estimated)

The solution of this differential equation yields the logistic curve:

$$\frac{m}{n} = \left(1 + e^{(-\alpha-\beta t)}\right)^{-1}$$

where β = the speed of diffusion parameter, and

α = a constant which describes the curve's displacement in time.

A simple logarithmic transformation of this function yields the equation:

$$\log \frac{m}{n-m} = \alpha + \beta t \, .$$

This equation can be estimated using time series data on one innovation, in one industry, to yield estimates of α and β. The estimate of β can in turn be used to calculate the time it takes to go from, say, $\frac{m_1}{n}$ to $\frac{m_2}{n}$ diffusion.*

The model is useful for its predictive power and for interindustry comparisons. For example, the econometric evidence can be used to forecast future diffusion once the speed parameter, β, is calculated. Secondly, the β's, which are estimated separately using time series data for each industry, can be compared across industries using cross-section data to determine whether and the extent to which various industry and technological conditions influence the speed of diffusion of new technology.

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$$t_2 - t_1 = \frac{\log \frac{m_2}{(n-m_2)} - \hat{\alpha}}{\hat{\beta}} - \frac{\log \frac{m_1}{(n-m_1)} - \hat{\alpha}}{\hat{\beta}}$$

$$= \hat{\beta}^{-1} \log \frac{m_2(n-m_1)}{m_1(n-m_2)}$$

Thus, the speed of diffusion depends only on the value of $\hat{\beta}$.

Mansfield postulated that the speed of diffusion of new technology is a function of various characteristics of the technology, characteristics of the using industry, and environmental conditions. Thus, the speed of diffusion parameters obtained by subjecting the logistic model to econometric estimation is assumed to be a function of the variables just described:

$$\hat{\beta} = a_0 + a_1X_1 + a_2X_2 + a_3X_3 \ldots\ldots + \varepsilon.$$

Here, the X's are various industry, technological, and environmental variables that are hypothesized to affect the rate of diffusion. Estimation of these a_i's using cross-section data enables forecasters to predict the speed of diffusion and policymakers to assess the impact of alternative market conditions on the rate of diffusion of new technology.

The general format of diffusion research has been to study the speed of diffusion of one or more distinct innovations, in one or more industries, in one or more states, regions, or countries. Thus, to the extent that multiple innovations are studied in the same industry, characteristics of the technology that might affect the speed of diffusion can be isolated. When the same innovation diffuses in several industries, the importance of characteristics of the using industry such as its market structure can be determined. Similarly, cross-country comparisons may shed light on the question of whether international productivity differences stem in part from differences in the speed of diffusion. In addition, such knowledge will indicate the extent to which empirical evidence gathered from other countries is relevant to estimating the speed of diffusion in the United States. The next section below summarizes the empirical results on the speed of diffusion of new technology. The following section describes the results on the determinants of the speed of diffusion.

RESEARCH RESULTS

SPEED OF DIFFUSION

Several economists have undertaken research to estimate the speed of diffusion using the methodology described above. Edwin Mansfield estimated the speed of diffusion of 12 innovations in the bituminous coal, iron and steel, beer brewing, and railroad industries using the logistic curve model. The speed of diffusion parameters was estimated using time-series data on each innovation. The logistic curve fit the data extremely well with a mean R^2 of .95. A common way to express the speed of diffusion is the time taken to go from 5 percent diffusion to 50 percent diffusion.* The results of

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*This formulation is necessary since the logistic curve only assymptotically approaches zero and one.

Mansfield's 12 innovations indicate that the mean diffusion time from the point at which 5 percent of firms have adopted (e.g., one typical firm in an industry of 20 firms) to 50 percent diffusion is about 12 years. Most innovations took 8 to 15 years to diffuse using this definition.*

Romeo estimated the speed of diffusion of one innovation, numerically controlled machine tools in 10 different industries (listed below) (see Anthony Romeo, 1975). As can be seen, there were significant interindustry differences in the speed of diffusion. The mean time between 5 and 50 percent diffusion was about 9 years.

	Speed of Diffusion Φ	$\overline{R}^2$	Time (in years) 5% to 50%
Aircraft Engines	.264	.93	11.2
Airframe	.266	.99	11.1
Printing Presses	.283	.99	10.4
Coal Mining Machinery	.328	.92	9.0
Digital Computers	.354	.97	8.3
Large Steam Turbines	.403	.99	7.3
Machine Tools	.643	.83	4.6
Farm Machinery	.193	.63	15.3
Tool and Die	.417	.69	7.1
Industrial Instruments	.643	†	4.6
Mean			8.9

†Too few observations to compute.

Several other researchers have estimated the speed of diffusion of new technology using similar or identical methodology. Simon investigated the diffusion of 23 process innovations in the chemical industry. Griliches' primary work explored the diffusion of hybrid corn by state and by crop reporting district. Hsia, again using Mansfield's methodology, estimated the speed of diffusion of 26 innovations in the plastics, textiles and garment, and electronics industries in Hong Kong (Ronald Hsia, 1973). In all of these studies the logistic curve appears to fit quite well. While the industries chosen for study are by no means random or representative, they are very broad based. Further, by almost any standard the speed of diffusion is typically quite slow. For slightly more than half of the innovations reported, the time from 5 to 50 percent diffusion exceeds 10 years. The next section describes the recent empirical evidence concerning the determinants of the speed of diffusion.

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*Diffusion is measured as the percentage of firms that have introduced an innovation, regardless of the scale on which introduction was made. Most introduction, however, had to be made on a fairly large scale. See Mansfield (1968), pp. 133-154.

DETERMINANTS OF THE SPEED OF DIFFUSION

Neoclassical economic theory is for the most part concerned with comparative statics; it says little about the process of transition from one equilibrium to another. However, one would expect that the single most important factor affecting the speed of diffusion would be the profitability of an innovation. Therefore, some measure of profitability, either a direct measure or a payback period, should be included as an explanatory variable in any regression attempting to explain the speed of diffusion. Due to the fact that profit-maximizing firms operate in environments of imperfect information, are inherently risk averse, and may face financial or liquidity constraints, and also that investments are lumpy or indivisible, other factors must be considered. In particular, due to the fact that the implementation of many process innovations may require large capital investments, the size of required investment relative to the size of a firm may be an important determinant of the speed of diffusion. Secondly, since the innovation is often embodied in durable capital equipment, the normal life of the asset being replaced might be included. Further, since investment takes place faster in a growing market than in a stagnant one, the rate of growth of the using industry or industries may be relevant. Fourth, since information concerning new innovations is imperfect, the R&D intensity may be a proxy for the quality of information available. Finally, market structure variables may be important determinants of the speed of diffusion. These considerations suggest that profitability, size of investment required, normal life of asset replaced, rate of growth of using industries, R&D intensity, and market structure might be included as possible explanatory variables in any regression attempting to explain the speed of diffusion.

These a priori expectations are largely borne out by the empirical research done by several economists. Mansfield found in his sample of 12 innovations in 4 industries that the only statistically significant determinants of the speed of diffusion were profitability and required investment outlay relative to firm size. Profitability is measured by the ratio of the required payout period divided by the actual payout period. Investment is a function of the assets of the company. When the durability of old equipment replaced by the innovation is added as an independent variable, it enters with the correct sign but is not significant. Similarly, market growth rate in the using industry enters with a positive sign but the coefficient is not significant. There is some tendency for the rate of imitation to increase over time, but the coefficient was not found to be significantly different from zero. Although the sample of industries is small (n=4), Mansfield tentatively concludes that the results are broadly consistent with the hypothesis often advanced that the rate of imitation is higher in more competitive industries.

Hsia essentially duplicates Mansfield's methodology using as a sample 26 process innovations in the plastics, textile and garment, and electronics industries in Hong Kong. Again, the estimated speed of diffusion is positively and significantly related to profitability and negatively and significantly related to required investment. It appears that the sample of three industries may have been too small to make conclusions about market structure.

Romeo investigated not only the effects of profitability on the speed of diffusion, but also industry variables such as market structure. Market structure was measured using two variables: N, the number of firms in the industry, and V, the variability in firm sizes (the variance in the natural logarithm of total employment).* The R&D sales ratio, R, was included as a proxy for an industry's responsiveness to new innovations, and G as a scale variable. His regression, using data on numerically controlled machine tools in 10 industries, produced the following results:

$$\ln \hat{\beta} = \underset{(4.512)}{.864 \ln \Pi} + \underset{(4.130)}{.14 \ln N} - \underset{(-2.604)}{.111 \ln V}$$

$$- \underset{(-4.728)}{.327 \ln G} + \underset{(3.413)}{.080 \ln R} \qquad \bar{R}^{2} = .74$$

As can be seen, all coefficients are significantly different from zero. Interestingly, market concentration has a depressing effect on diffusion. The greater the number of firms and the more equal their sizes the faster the rate of diffusion. Also, industries with a higher R&D/sales ratio experience faster diffusion as do smaller industries.

More recent work on the diffusion of process innovations has been done by S. W. Davies (Davies, 1979). He criticizes the Mansfield type models on both theoretical and empirical grounds and develops a more complex model of diffusion based on individual firm decisionmaking. His results, however, both in terms of the estimated speeds of diffusion and the determinants of diffusion, provide strong support for Mansfield.

Davies constructs a model based on individual microeconomic decisionmaking. In it he distinguishes between major and minor innovations where major innovations are assumed to follow a cumulative normal diffusion path rather than a logistic curve. For "major" innovations, the typical time from 5 to 50 percent diffusion is about 11 or 12 years. For the minor innovations, the typical diffusion time is considerably longer.

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*These two are closely related to the Herfindahl Index.

Davies then estimates the determinants of the speed of diffusion in a second stage process similar to Mansfield's. His typical results are as follows (standard errors in parentheses):

$$\hat{b} = \overset{\text{(unreported)}}{\text{constant}} - \underset{(.071)}{.189\sigma^2} - \underset{(.07)}{.104 \log N} - \underset{(.163)}{.819 \log \Pi} + \underset{(.586)}{2.390 \log LI} \tag{1}$$

$$\hat{b} = \overset{\text{(unreported)}}{\text{constant}} - \underset{(.064)}{.245 \log N} - \underset{(.230)}{.794 \log \pi} + \underset{(.779)}{2.909 \text{Log } LI} \tag{2}$$

$$\hat{b} = \overset{\text{(unreported)}}{\text{constant}} - \underset{(.061)}{.271\sigma^2} - \underset{(.200)}{.834 \log \Pi} + \underset{(.940)}{2.321 \text{Log } LI} \tag{3}$$

These results indicate that profitability is strongly related to diffusion speed,* as is the labor intensity (LI) of the industry. Concerning market structure variables, diffusion appears to be greater with smaller numbers of equal sized firms. (LogN is not significant in the first equation, presumably due to collinearity with σ^2, the variance of the logarithm of firm size.)

These results appear to be in contrast to those of Romeo on the effects of market structure. Whereas they both concluded that uneven firm sizes, that is, high variances of the logarithms of firm sizes, leads to slower diffusion, they come to opposite results with respect to number of firms. Romeo reports that the speed of diffusion is strongly positive and significantly related to the number of firms, while Davies reports a negative relationship, also with a high degree of significance.

The discrepancy appears to be resolved when one considers the number of firms in each sample. Davies reports that in only one industry out of 22 is N less than 20. Romeo does not report the value of N, but his sample includes airframes, aircraft engines, digital computers, and farm machinery, where N is probably considerably smaller than 20. Thus, it may well be that there is a nonmonotonic relationship between the number of firms and the speed of diffusion where the speed of diffusion first increases and then decreases with the number of firms in the sample. The two researchers may simply have estimated two nonoverlapping portions of the same curve. Thus, it appears probable that maximum diffusion occurs in industries with one to two dozen roughly equal sized firms.

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*Because of the measure Davies uses for his profitability variable, the negative coefficient indicates that the rate of diffusion increases with the profitability of the innovation.

In conclusion, it appears that both the logistic curve and Davies' cumulative normal curve for major innovations fit the data quite well. By almost any standard, the diffusion of new technology appears to be a very slow process. A majority of the innovations surveyed reached 50 percent diffusion in 10 years or more. This long period of diffusion is particularly noteworthy since most of these innovations were chosen after the diffusion process was completed, that is, only successful innovations were chosen for study. Considering this fact, the ex-ante prediction of a diffusion rate for a new innovation might be slower.

It is apparent from available empirical research that the rate of diffusion is very strongly and significantly related to profitability. Also, there is some evidence that the speed of diffusion is negatively related to required investment, positively influenced by the rate of growth in the using industry, and that diffusion may be quicker in competitively structured (but not atomistic) industries.

CRITICISMS OF DIFFUSION LITERATURE

The econometrics literature on the diffusion of innovation has been criticized for a number of flaws or omissions. The most important of these criticisms is that diffusion rates are likely to be quite different in different market segments, depending on the size and configuration of potential adopters. Secondly, the population of adopters is difficult to ascertain and in practice may change dramatically with changes in the technology.

The population of potential adopters is an empirical matter to be researched carefully -- not simply a matter of SIC classification. Econometricians can make serious errors if they ignore the fact that not every firm in the population of potential adopters will necessarily have the same production function. Rosegger (1979) indicates that abstract analyses of continuous casting in the steel industry suggest substantial savings in steel production costs through reduced capital investment per ton, plant space savings, lower energy, labor and maintenance expenses, and improved quality and yield. However, despite these economic arguments for rapid diffusion, a careful analysis of existing plant configurations reveals several barriers to speedy diffusion.

The benefits just described can only be achieved through complete plant retrofits or in greenfield expansions. However, the scale and technical characteristics of the continuous casting technology are such that the benefits of retrofit can only be attained in small, billet casting plants. In contrast, the adoption of continuous casting on an incremental basis would lead to cost increases, particularly in large integrated mills. Even under favorable installation conditions, the economics of continuous casting would depend on a number of plant-specific technology factors, such as the size of the production run and the quality specifications of the steel being produced.

A second major criticism of the economics literature on diffusion is that the studies do not sufficiently recognize that important innovations emerge in a variety of forms in their early development and often continue to change over time. Gold (1981) indicates that measured differences in diffusion rates may be due to the extent of ongoing technical change in a specific process technology rather than to particular characteristics of the adopter. For example, continuous performance improvements were made in numerically controlled machine tools as they were being diffused. Such changes expanded the population of potential adopters as they occurred. Thus, analyses that assume a static population of adopters could lead to faulty conclusions on diffusion.

A third frequent criticism of econometric studies on diffusion is that too much reliance is placed on variables such as profit. Data necessary to estimate profitability are often grossly inadequate. Further, the informational uncertainties and risks facing a decisionmaker are often so great that they overshadow capital budgeting estimates of profit. Rather, adoption decisions are based more on value orientations of influential managers and on engineering evaluations of changes in output to input ratios and not on capital budgeting estimates.

Economists, however, have persistently found that profitability is a positive and significant determinant of diffusion rates. Further, variables such as required investment relative to firm size have also been found to be significant. It may be true that measures of profitability may be insufficient to make accurate forecasts of diffusion, or that many other non-economic variables are also important determinants of diffusion rate. However, it cannot be said that economic variables such as size of investment and profitability are not important determinants of the speed of diffusion.

Finally, all econometric forecasting approaches rely on the assumption that the preferences and institutions that underlie the postulated relationships remain stable over the forecast horizon. This assumption may not be borne out in the case of foreign competition which has intensified in recent years. Although the econometric approach to forecasting diffusion can assist NBS by pointing out important influences on diffusion, considerable caution should be exercised in accepting quantitative predictions of diffusion rates based solely on econometric studies. Rather, a diversity of factors, many of which cannot be quantified, influence diffusion rates. We now turn to an examination of these factors.

7

DIFFUSION -- INTERNAL AND EXTERNAL FACTORS

The literature on industrial innovation spans several disciplines and may be broadly divided into research that emphasizes factors external to the firm to explain and predict technology adoption and research that emphasizes factors internal to the firm. Tables 7-1 and 7-2 present a summary of the factors linked to the adoption of industrial technology in the literature we reviewed. We now review studies of each of the influences on diffusion listed in the two tables.

EXTERNAL FACTORS INFLUENCING DIFFUSION

FEAR OF OBSOLESCENCE AND INDUSTRY LIFE CYCLE

Pre-Schumpeterian thinking on innovation and diffusion held that competition in the marketplace would hasten the adoption of new technologies. The introduction of a new product or process by one firm would threaten rivals with technological obsolescence and a loss of competitiveness in cost.

Abernathy (1976) conducted a comprehensive case study of technology change in the automobile manufacturing industry. He closely examined the adoption of 20 product and process innovations related to automobiles that occurred at various times from the 1920s to the 1970s. Abernathy's overall conclusion from his analysis is that the entire process of technology change in an industry has to be understood in terms of the overall life cycle of the industry. Fear of obsolescence was found to be an important inducement to technology diffusion. However, the importance of this inducement to diffusion will vary over the industry's life cycle.

Table 7-1

LITERATURE DISCUSSING HYPOTHESIZED INFLUENCES ON DIFFUSION: EXTERNAL* INFLUENCES

INFLUENCES ON FIRM	SOURCE
Threat of premature obsolescence	Abernathy, 1976 and Gold, 1981
Industry life cycle	Abernathy, 1976
Profit or appropriatability	Romeo, 1975 and Gold, 1981
Size of the investment	Mansfield et al., 1982
Market segmentation	Wind, Robertson & Fraser, 1982 and Rosegger, 1979
Market shifts	Abernathy, 1976
Technology shifts	Gold, 1981; Abernathy, 1976; and Jacobsson, 1982
Macroeconomic & tax policy	Cordes, 1980
Industry structure	Romeo, 1975; Duke & Brand, 1981; Wind, Robertson & Fraser, 1982; Thomas & LeHeron, 1975; Gort & Kleper, 1982; and Abernathy, 1976
Innovation cycles	Girifalco, 1982
Innovation synergy	Boretsky, 1980
Marketing aggressiveness	Duchesneau, 1976 and Mansfield et al., 1982
Skilled worker mobility and attitude	Masterson & Hayward, 1979; Jacobsson, 1982; Czepiel, 1975; Mansfield et al., 1982; and CRA, 1980

*External to the firm.

SOURCE: Charles River Associates, 1983.

Table 7-2

LITERATURE DISCUSSING HYPOTHESIZED INFLUENCES ON DIFFUSION: INTERNAL* INFLUENCES

INFLUENCES ON FIRM	SOURCE
Firm size	Ray, 1969; Duke & Brand, 1981; Romeo, 1975; Mansfield et al., 1982; Marx, 1979; and Duchesneau, 1976
Fear of downtime	Romeo, 1975; Mansfield et al., 1982; and Abernathy, 1976
Work flow reorganization required	Ray, 1969; Duke & Brand, 1981; and Baker, 1982
Internal firm structure	Abel, 1981 and Baker, 1982
Ability to control transition costs	Abernathy, 1976
Knowledge of senior managers	Adams & Dirlam, 1966; Gold, 1982; Abernathy, 1976; and Mansfield et al., 1982
X-inefficiency	Liebenstein, 1969
Personality of firm	Gold, 1981 and Gort & Singamsetti, 1978
Habit change requirements	Mansfield et al., 1982

*Internal to the firm.

SOURCE: Charles River Associates, 1983.

Abernathy's "model" of the link between industry life cycle and the adoption of innovation maintains that the early period in an industry's life cycle is characterized by frequent and often radical technology changes in both products and processes, with product changes predominating. In this period the production processes of the new industry are set up to be flexible, utilizing general-purpose equipment and readily available materials, in order to be able to respond to rapidly changing customer product specifications and product innovations by competitors. In the early period of the life cycle, the fear of obsolescence will operate on both suppliers and users of the new industry's output to stimulate rapid adoption of the new technology.

In the mature stage of an industry, the rate of diffusion of new technology can continue to be rapid because of competition and the fear of obsolescence. However, productivity gains from even the rapid adoption of an innovation will be modest because innovations will now tend to be incremental rather than major. Abernathy posits that substantial productivity gains come in a mature industry only through the cumulative effects of a number of incremental innovations, or from the "shock" effect of an unexpected and radical innovation introduced on the demand or supply side of the market by an entirely new group of market entrants.

Abernathy's point about the need for an external "shock" to spur innovation, diffusion and productivity growth in a mature industry would appear to apply directly to the machine tool industry and the adoption of FMS technologies. The machine tool industry in the United States is thought to be both mature and slow to innovate. Thus, if this industry is to become the supply side of the emerging FMS equipment industry, some type of shock may be required to reverse the slow pace of product innovation that has characterized this industry for the last few decades.

According to Bylinsky (1983), a substantial shock is already occurring in this industry due to the rapid advances being made in the production and use of FMS technologies in Japan and the expected increase in the sales of Japanese FMS equipment in the United States. However, a successful adaptive response by U.S. machine tool producers and potential FMS users is by no means assured. Rather, such shocks are a necessary but not sufficient condition to insure the desired increase in innovation, diffusion, and productivity.

Gold (1981) makes an additional point about the fear of technological obsolescence as an influence on the rate of diffusion. He asserts that the static concept of innovation needs to be replaced with a more dynamic one since most innovations undergo continuous and sometimes rapid modifications as their diffusion proceeds. Gold maintains further that continuous modification of a particular industrial process innovation may actually slow down its diffusion because of the fear that some potential adopters may have about committing themselves to the new technology too soon and becoming outmoded very rapidly by further modifications in the technology. In other words, the kind of causality that Gold is concerned with will work in the opposite direction to the causality with which Abernathy is concerned. However, it may be true that fear of obsolescence operates to spur the adoption of product innovations and hinder the adoption of process innovation.

The fear of obsolescence may be particularly applicable to the near-term diffusion of FMS technologies into the small machine shops. The adoption of FMS will often represent a substantial investment for small machine shops relative to their total capitalization. Furthermore, FMS technologies are likely to undergo continuous and rapid change over the next two decades. Therefore, the fear of premature obsolescence may emerge as an important factor in limiting the diffusion of FMS technologies into machine shops in the United States in the near term. This in turn could adversely influence the international cost competitiveness of industries that rely on the output of the nation's machine shops. These customers may turn to the Japanese to supply machined parts, thus putting additional pressure and fear of obsolescence on U.S. machine shops.

PROFITABILITY AND APPROPRIABILITY

The econometrics literature on diffusion strongly supports the hypothesis that expected profits play a major role in determining the rate of adoption of a new technology. The data sets frequently utilized by econometricians are not precise enough to enable us to use established econometric models of diffusion to predict the rate of diffusion of a particular innovation into the future. It may also be true that managers themselves may have too imprecise a notion of profits to base their decision to adopt an innovation mainly on the criterion of expected profitability. Instead, managers may be relying more on other criteria, perhaps with profitability estimates serving as a constraint of some sort (e.g., as a satisfying rule). However, it does not follow that the econometric models have not increased our understanding of the factors that have influenced the historic rate of adoption of technologies that are now fully diffused, however poor the proxies used in the equations to represent these factors. The fact that profitability is persistently found to be a factor influencing diffusion rates, despite poor data, suggests that managers must use this criterion in their decisionmaking, whether implicitly or explicitly. Limitations in the accuracy of the data on expected profits may, however, impair our ability to forecast accurately the rate of diffusion of a new technology.

SIZE OF INVESTMENT

The econometrics literature has found that the size of the investment required to adopt a new technology relative to the size of the adopting firm is an important influence on technology diffusion. Such a finding suggests that relative size of the investment be an important determinant of the diffusion of FMS technologies, particularly into small, poorly capitalized machine shops. However, influences like size of the investment required have to be evaluated in the context of appropriate market segments, a topic that we now return to briefly.

MARKET SEGMENTATION

In the last chapter we discussed Rosegger's view (1979) that analyses of technology diffusion should take into consideration the fact that there are probably several segments in each industry with different propensities to adopt a new technology. In his case study of the adoption of continuous casting, Rosegger found different diffusion rates in different market segments, depending on technology criteria such as the configuration of equipment in place and differences in the end products being produced across firms in the adopting industry.

While Rosegger's findings deal with the adoption of CT scanners in hospitals, and are not directly applicable to the adoption of FMS technologies, they do confirm the point that market segmentation should be considered in analyzing FMS market penetration. The importance of this conclusion is reinforced by the fact that the machine tool industry appears to be highly segmented, with a high degree of specialization among machine shops in both products and production processes (Marx, 1979).

MARKET AND TECHNOLOGY SHIFTS

Gold (1981) has pointed out that, in general, diffusion is likely to be influenced by technological change that occurs more or less continuously in many areas of industrial technology. As a specific and relevant example, Jacobsson (1982) points out that the cost and unreliability of electronic components hindered the diffusion of numerically controlled machine tools until the use of minicomputers in association with numerically controlled machine tools was introduced in the early 1970s. Diffusion was expedited further with the use of microcomputers with the numerical control unit in the mid-1970s.

While Gold and Jacobsson address the importance of technology shifts introduced from the supply side of the market, Abernathy (1976) stresses the importance of shifts in demand in influencing the adoption of new technology. Citing examples of several shifts in automobile product and process technology, Abernathy makes the point that many so-called innovations had very early design origins and were only widely adopted when shifts in preferences or market demand provided the appropriate signal. For example, Abernathy maintains that the air-cooled engine popularized after World War II in the Volkswagen "Beetle" was first commercially introduced in 1895. Thus, a sudden shift in the rate of adoption of a new innovation can occur entirely due to a shift in the needs or tastes of the demand side of the market.

Following the lead of Jacobsson and Abernathy one may begin to conjecture how market and technology shifts could influence the diffusion of FMS technologies in the future. For some time the rate of technical advance in FMS technologies may be rapid while the diffusion of these technologies may be slow. This initially slow rate of diffusion will occur due to the threat of premature obsolescence (Gold, 1981). However, once technology trends in FMS become clearer and the threat of international competition grows even more ominous, a rapid rate of adoption of FMS in the United States may follow as fear of obsolescence induces a shift in demand (Abernathy, 1976). In other words, firms strive to strike a balance between adopting a new technique too early and too late. In the case of FMS technologies that happen to be in the early part of their life cycle, but are very important for international competitiveness, a slow rate of adoption may occur in the near term followed by a rapid rate of adoption, perhaps in the early 1990s.

MACROECONOMIC AND TAX POLICIES

Joseph Cordes set out the linkage between industrial technology innovation (and, we assume, diffusion) and the macroeconomy in a recent Report to the National Academy of Science (1980). Cordes points out that an unstable and stagnant economy discourages the adoption of new industrial technology for three reasons:

- Demand for new capital goods falls;
- Small, technology-based firms cannot obtain the funding they need; and
- If inflation rates are high, businesses adopt short-run horizons and are less willing to take the longer-term risks that are often associated with new and innovative industrial technologies.

Although NBS cannot directly influence macroeconomic conditions, it can influence some of the factors above. First, although demand for new capital goods falls during recessions, NBS research may influence the composition of this demand. Secondly, the willingness of capital markets to lend funds to firms manufacturing or using FMS may be influenced by NBS. For example, a president of a leading robot systems company told CRA interviewers that the existence of NBS research in robotics was instrumental in his ability to fund the firm's initial operations succesfully. Finally, demonstration of future technologies by NBS may aid firms in taking what would otherwise be considered a prohibitive long-term risk.

INDUSTRY STRUCTURE

A number of researchers hold that industry structure is generally an important determinant of technology diffusion. In the case of the emerging

FMS industry, one can readily conjecture that competition will be keen in the FMS equipment supplying industry due to both the diversity of firms that are currently carrying out research in the area and the likelihood of intense competition from foreign FMS equipment suppliers. Diffusion is thought to be faster in a competitive market since firms are more inclined to adopt a new method of production when there is a likelihood that their competitors would enjoy a cost advantage if they do not.

In applying these principles to the case of the diffusion of FMS technologies it is important to maintain the distinction between the demand and supply sides of the FMS equipment market. For example, competition on the demand side of the market is likely to be strong in many segments (e.g., auto assembly) and therefore is likely to provide a strong inducement to the rapid diffusion of the FMS equipment. On the other hand, competition is also likely to be intense on the supply side of the FMS equipment market and this may discourage some suppliers from developing more innovative FMS equipment because of the expectation of low returns on the R&D investments necessary. Such may turn out to be the case in segments of the U.S. machine tool industry that have historically been slow to develop new product designs.* Therefore, when considering the impact of market structure on the diffusion and productivity impacts of FMS equipment, it will be important to be precise about the type and vintage of the FMS equipment being considered. It will also be important to consider the role played by foreign equipment suppliers and by users when assessing the impact of industry structure on diffusion and productivity.

MARKETING AGGRESSIVENESS

The aggressiveness of the marketing of a new industrial technology will have a positive relationship to the speed of diffusion of that technology. Duchesneau (1976) reports the results of a study of the rate of adoption of 12 incremental, automation technologies at 5 shoe manufacturing firms over a 12-month period. Duchesnau's description of the shoe industry makes it similar to the machine tool manufacturing industry. As in the machine tool industry, the shoe industry is composed of a few large producers and many small producers. The small producers are slow to adopt new innovations, are facing strong competition from imports, and have not experienced substantial increase in productivity in some time.

Duchesneau found that firms in the shoe industry are slow to automate because they view the market with a very short-run time horizon dictated by frequent style changes. Furthermore, differences in leather grades and irregularities in foot sizes pose several design constraints on suppliers of automation technology. Therefore, technological change is slow and in order to lower risk, new shoe manufacturing equipment is typically leased rather than purchased.

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*See CRA (1982) for a description of the U.S. machine tool industry.

To carry out his analysis, Duchesneau first fitted an econometric model similar to the type employed by researchers like Mansfield and Romeo. He claims to have gotten sensible results despite his finding that most of the managers in the shoe industry are incapable of calculating a pay-out period or performing a present value analysis. He also tested an "organizational" model. In this latter model the rate of adoption of a specific technology (geometric grading of shoe sizes) was fitted to ownership, the number of occupational specialties at the plant, the amount of contacts by equipment salesmen, the ratio of managers to employees, and the education level of the operating manager.

According to Duchesneau, the organizational model fit better than the econometric model. However, only ownership, firm size, and sales contacts turned out to be significant in the organizational model. The finding that frequency of sales contacts did increase the rate of adoption reinforces the assertion made in Mansfield et al., (1982) that marketing aggressiveness by sellers will be an important determinant of diffusion of FMS technology.

SKILLED WORKER MOBILITY AND ATTITUDE

A great deal has been written concerning the importance to diffusion of the attitudes of skilled workers, particularly unionized workers, toward automation technologies, and also of interfirm mobility among skilled engineers. This literature suggests that the attitude and mobility of workers who will have to utilize FMS technologies are likely to be important determinants of its rate of diffusion and thus its overall productivity impact.* In particular, intraindustry communication channels are found to be an important stimulant to diffusion despite widely held views that such channels are not well developed due to the geographic dispersion of plants and the need for corporate secrecy. Note, however, that such a finding does not rule out the importance of economic and other factors.

NBS might draw some insights from the literature that stresses interfirm mobility, attitudes, and intraindustry communication channels to explain and predict diffusion. Workshops sponsored by NBS and dealing with the design and use of FMS, or direct-contact opportunities at the FMS test facility at NBS, will expedite its diffusion by changing the conceptual framework of potential adopters of FMS through the dissemination of the findings of NBS' research and the research of others. Such workshops or direct contacts will also facilitate the kind of interfirm social interaction that Czepiel (1975) found was an important determinant of the diffusion of continuous casting technology. Unfortunately, we do not see any direct relevance or role for NBS in the area of interfirm mobility of key personnel. Apparently the degree of mobility depends on the culture and habits of workers in an industry, as well as the dynamism of the technology. Such cultural factors are probably beyond the influence of NBS.

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*Some of this literature is described in Mansfield et al., (1982). CRA's comprehensive analysis of the semiconductor industry (1980) discusses the role of interfirm mobility in some detail.

INTERNAL FACTORS INFLUENCING DIFFUSION

FIRM SIZE AND FEAR OF DOWNTIME

The economic and other literature that we have examined consistently points to firm size as an important determinant of the adoption of a new technology by a particular firm and thus of the technology's diffusion across an industry. Firm size seems to be positively correlated with diffusion although other factors such as industry structure can modify this relationship. Firm size is particularly relevant in the context of the size of the investment required to install the new innovation in a plant. Thus, investment costs relative to firm capitalization frequently are significantly and negatively correlated with diffusion. In general, the econometrics literature shows that moderate industry concentration and some barriers to entry provide the best structural situation for innovation and diffusion. This finding is also confirmed to an extent by the low rate of innovation in both the machine tool (CRA, 1982) and the shoe industry (Duchesneau, 1976). Both of these industries are intensely competitive and are dominated by small manufacturing establishments.

Other papers echo this finding but express it in different terms. Thus, Ray (1969) points out that the fear of equipment downtime was a significant factor inhibiting the diffusion of numerically controlled machine tools in Europe. Duke and Brand (1981) reach the same conclusion regarding the machine tool industry in the United States, which they predict will make FMS equipment but will not utilize it due to fear of the adverse production and cash flow consequences of downtime. Marx (1979) points out that smallness and specialization have contributed to the slow pace of technological innovation in the machine tool industry because small firms lack the funds to do the R&D necessary to prepare themselves for the adoption of equipment such as numerically controlled machine tools. Duchesneau's (1976) study of shoe manufacturers found that small-sized operations in that industry were reluctant to adopt new technologies. All of these papers seem to be addressing the issue of risk as a significant inhibitor of diffusion in small firms. The strength of this inhibition seems to decrease as firm size increases. The fear of downtime may be especially significant in the case of the small machine tool manufacturers in the United States. However, increasing foreign competition may offset this negative influence somewhat in firms of all sizes by stimulating adoption to avoid obsolescence.

The U.S. machine tool industry is likely to be a major target market for FMS technologies. However, we have just seen that this industry is likely to be risk averse with respect to the adoption of FMS because it is dominated by small firms. This risk aversion is likely to be a substantial inhibitor to the diffusion of FMS technologies. Furthermore, this inhibition is likely to be reinforced by the fear of premature technological obsolescence if FMS technologies are evolving rapidly. Therefore, the development and dissemination of credible information that fully characterizes the performance and reliability of the various configurations of FMS equipment will greatly expedite the diffusion of these technologies. We strongly recommend that NBS consider its role in disseminating technical information when planning and carrying out its programs in FMS technology. NBS, in fact, may have a unique role to play in disseminating technical information to industry because it is perceived as a neutral expert (CRA, 1983).

FMS equipment suppliers may support this need for equipment characterizations. James Baker, Executive Vice President of General Electric's Technical Systems Sector, has pointed out that capital spending for FMS technologies has been delayed more by a lack of confidence in the equipment available rather than by the economic outlook (1982). He goes on to point out that the potential user of FMS will have to be drawn "a roadmap showing where the biggest productivity wells in their plants are and how to tap them without going broke in the process." Thus, if Baker's point is correct, FMS equipment manufacturers as a whole should increase their sales if an independent and unbiased agency provides potential users with credible information about the performance characteristics and methods for determining the best applications for the various classes of FMS equipment on the market.

R&D EXPENDITURES

The econometrics literature (e.g., Romeo, 1975 and Mansfield et al., 1982) points to a significant and positive relationship between the diffusion of industrial technology and expenditures on R&D by the adopting industries. As Romeo points out, the more R&D that is done by potential adopters, the greater their familiarity with the innovation. Familiarity should, ceteris paribus, lead to faster adoption. Firms which engage in R&D are not only likely to be more knowledgeable concerning recent innovations, but are also likely to be more ready adopters of innovations whether developed internally or externally. The emerging FMS industry is composed of firms of diverse sizes and with diverse parent industries. Furthermore, FMS technology is well known to be in need of more fundamental research, particulary on sensors and control hardware and software. Therefore, we believe that R&D expenditure levels by firms on the supply side of the FMS market will be an important determinant of the diffusion of FMS technologies.

COST CONTROL AND WORK FLOW ORGANIZATION

Abernathy (1976) makes the point that cost considerations will slow the adoption of innovations when technological progress is rapid in specific areas of process technology. Since the evolution of FMS technologies is likely to be very rapid over the next two decades, cost control imperatives will inhibit the diffusion of each generation of FMS equipment to some extent. If FMS technologies are installed too rapidly, a firm's cash flow can be depleted by the large expenditures made for equipment.

The need for extensive work flow reorganization can also impede the adoption of FMS technologies. Ray (1969) pointed out that this factor was an important inhibitor of the diffusion of numerically controlled machine tools in Europe. Baker (1982) makes the same point indirectly when he forecasts that the adoption of robotics within an antiquated manufacturing operation will be a "waste of the robot's time and the user's money."

The reorganizations of work flow that will be required to adopt FMS technologies successfully and gain their full productivity benefits are likely to be very extensive in many plants. Baker (1982) stresses that successful adoption of FMS will require the kind of total reorganization that will result in the integration of FMS hardware with the technology of computer-aided design (CAD). He points out that token automation steps like installing one or two robots will often not be a wise use of capital resources. According to Baker, the kind of plant reorganization that will be needed will be one that fosters the smoothest transition from islands of automation to linked islands and finally to an integrated manufacturing system. Gold (1982) goes even further than Baker by suggesting that the full productivity benefits of FMS will occur only when management considers fully the impact of the adoption of FMS on the organization of production as well as on additional factors such as product mix, product quality, product prices, and plant capacity utilization. Undoubtedly, numerous feedback loops will exist between plant organization, FMS, and the additional factors that Gold mentions. Remaking such fundamental decisions is likely to lead to substantial reorganization of operations in some firms. To the extent that broad reorganizations are required, diffusion of FMS will be inhibited.

If firms reappraise their product markets as FMS diffuses, they, as well as NBS with its standards and measurements functions, might wish to consider the recommendations made recently by Professor Nam Suh, Director of the Productivity Lab at the Massachusetts Institute of Technology. Dr. Suh's view is that the whole issue of the nature and number of parts to be produced in machine shops needs to be thoroughly reexamined. Specifically, he thinks that considerable productivity gains can be made by greater simplification in design and the standardization and mass production of many of the custom-designed, machined parts not produced in batch lots. This would simplify machinery and vehicle design, and save substantially on materials costs embodied in industrial equipment. It would also lead to economies in machine shop production through the processing of larger production lot sizes. Such changes would reduce materials cost and the extent of batch manufacturing relative to larger-scale production, thus raising overall industrial productivity.

In this view, firms and researchers have been attacking the wrong target in seeking productivity gains by trying to make batch manufacturing more efficient. The alternative is to do less batch manufacturing. As a corollary, Dr. Suh sees a significant role for NBS if there is a movement toward simplified designs and standardized parts. Specifically, he envisions NBS playing a major role in determining the mechanical and other performance characteristics of standardized machine parts and designs.

NBS will not be involved in decisions about the internal structure of firms and the work flow of the organization. However, NBS' research on FMS technologies may lead to information that might assist firms in organizing themselves to make the smoothest transition to FMS technologies and to gain the maximum productivity benefits that these technologies offer. Therefore, once again we recommend that NBS carefully consider the role that it might play in expediting the diffusion of FMS technologies by directing its technical activities toward providing information to potential users. Further, NBS might eventually play a role in characterizing the mechanical and performance properties of standardized machine parts and designs as Dr. Suh has suggested.

FIRM STRUCTURE AND KNOWLEDGE OF SENIOR MANAGERS

Firms that are structured so as to involve top management in decisions regarding new technology are more likely to be successful in adopting new technology. This point was made by Abel (1981) with respect to new product innovations. Senior management involvement is also likely to be a positive influence both on the willingness of a plant to try out a new process and on the ability of the plant to make a successful transition to its full use. Management's involvement in process innovations will only be positive, however, if there is a fair degree of trust of management within the plant.

Mansfield et al. (1982) point out that the more knowledge senior managers have about a particular industrial innovation, the more rapid its diffusion is likely to be. Gold (1982) maintains that the basic lack of awareness of most industrial managements about the far reaching potential of FMS technologies may turn out to be the most important inhibitor to the diffusion of these technologies. He suggests that this lack of appreciation of the potential of FMS technologies results in part from the limited knowledge of such capabilities on the part of most of the senior engineers responsible for advising top management. He goes on to assert that the concentration of FMS equipment vendors in selling their equipment in bits and pieces will reinforce this particular inhibition to diffusion by leaving the equipment purchase decision in lower levels of the company. Thus the full set of opportunities and costs associated with the optimal use of FMS may not be appreciated by top management in some firms for some time.

Inhibiting factors to diffusion might turn out to be particularly important in some FMS market segments characterized by large plants that do not have a strong commitment to factory automation. In contrast, senior management is likely to be knowledgeable and heavily involved in small plants committed to automation and in large plant industries such as autos and aircraft that are automating as a deliberate strategy of responding to the challenge of foreign competition.

Once again, we see a potential role for NBS in the development and dissemination of knowledge related to FMS technologies. The views of Mansfield and Gold reinforce the point that lack of knowledge of the ramifications of a conversion to FMS and the apprehension that arises because of this lack of knowledge are likely to be key factors that slow down the diffusion of FMS technologies and thus limit their productivity impacts.

HABIT, PERSONALITY, AND X-INEFFICIENCY

Up to this point we have been considering what profit-maximizing managers and firms operating with full information will do when confronted with various incentives and disincentives to adopt FMS. Some analysts maintain that managers in some firms and industries do not conform to this paradigm. For example, Duchesneau (1976) maintains that shoe manufacturers were incapable as a group of carrying out present value calculations to evaluate investments. Adams and Dirlam (1966) suggest that the steel industry in the United States was slow to adopt the basic oxygen furnace long after its superiority to the open hearth furnace had been demonstrated. These authors seem to be faulting management, at least indirectly, for their tardiness in adopting new innovation. If a large number of managers in the industries that are potential users of FMS are in fact deficient in the skills and the motivation necessary to adopt new innovations successfully, the diffusion of FMS will be impaired. However, before such a hypothesis can be accepted, it is necessary to determine if these managers are deficient, or whether the decision faced by such managers is more complex than most outside analysts are able to observe.

Mansfield et al. (1982) point out that persistence in habits will inhibit diffusion. However, such persistence may be entirely rational when the full set of intrafirm circumstances are considered.

Gort and Singamsetti (1978) maintain that individual firms have a distinct personality that will affect the adoption of innovations. Specifically, a firm's personality will influence the discretionary choices that it makes with respect to the adoption of new processes or products. Firms considering the adoption of an innovation often face inadequate information. This leads to a situation where decisions are made more on the basis of the value orientation of influential managers rather than on hard economic calculations. Again we note the link between information and diffusion on the demand side of the market for a new technology.

The X-inefficiency literature (Leibenstein, 1969) offers still another explanation of why firms may be slow to adopt an ostensibly profitable technology. This slowness results in part from the fact that both workers and managers have some discretion about the level of effort they exert on the job. The term X-inefficiency refers to the difference between maximum output and the output at a plant that results from a lower level of effort. Essentially, the adoption of an innovation often requires workers and managers to move to a new equilibrium level of effort that is acceptable to both. Innovation will be inhibited if either the workers, managers, or both decide that their loss of utility during the transition to the new technology exceeds the gains in utility (if any) after the transition is made. Leibenstein maintains that some of the longer diffusion lags can probably be explained by X-inefficiency factors.

8

SUMMARY AND CONCLUSIONS

The issue of productivity has been an increasingly important one for businesses and government policymakers in recent years. In part, the attention paid to productivity is due to the decline in U.S. productivity growth, the substantial inroads that Japanese and European manufacturers have made in capturing a share of American manufacturing markets, and the sluggish growth rate of GNP. Claims are often made that computer-based automation systems are a major solution to the productivity problem. The purpose of this report has been to assess the role of the National Bureau of Standards in supporting industrial innovation and productivity growth through its activities in automated production technology.

PRODUCTIVITY

Productivity is defined as real output per unit of real input. When real output is divided by the relative contributions of all associated inputs, the resulting statistic is total factor productivity. The primary source of productivity growth is advances in knowledge which, in turn, are usually manifested in innovation.

The most obvious source of productivity benefits is the cost savings resulting from reductions in labor, including a reduction in the quality or quantity of the required inputs. Less obvious but equally important sources of cost savings resulting from flexible automation are reductions in raw materials, and inventory cost savings and quality improvements. Further, higher output rates and faster lead times may result from higher utilization rates of capital equipment. Finally, research on standards and measurement techniques will themselves lead to productivity increases through facilitating agreements between parties, lowering transactions costs, and perhaps increasing competition.

THE ROLE OF NBS

NBS' traditional role has been to develop the means and methods for making measurements, and facilitating the development of standards used in the private sector. Due to the fact that the research underlying measurement and standards is long term, risky, and cannot usually be sufficiently appropriated by firms or even industries, it is an area where there is likely to be substantial underinvestment by the private sector.

Over the last two decades NBS has become convinced that quality control systems in manufacturing would increasingly depend on characterization of the process, monitoring of machine parameters, and adaptive control. Such a development has led NBS to provide the means and methods of measurement where the measurements are embedded in the process of a Flexible Manufacturing System. Hence, NBS has embarked on the design, procurement, and installation of a fully-automated manufacturing facility in support of its measurement and standards responsibilities.

FLEXIBLE MANUFACTURING SYSTEMS

Flexible Manufacturing Systems can be described as a group of numerically controlled machines or other mechanized work stations, interconnected by a materials handling system and all controlled by a computer. FMS are expected to capture the efficiency advantages of hard automation along with the flexibility of small batch production. The major hardware in an FMS consists of NC machines and robots. Robots are used to load and unload parts, fixture these parts, and do assembly and inspections.

An integral part of a Flexible Manufacturing System consists of measurement and sensor devices. Robots must be able to respond appropriately to changes in their environment; hence vision and touch sensors are necessary. Similarly, sensors such as devices which measure tool wear must be incorporated into machining centers for these to operate in an unmanned environment. In sum, sensors and measurement devices can cut costs, increase the accuracy of machining, and eliminate the need for most human interaction.

Finally, individual workstations consisting of robots and machine tools, each incorporating sensors, must be integrated into a flexible cell. This integration requires both automated transfer systems which physically link workstations and complex computer control which electronically integrates the activities of each workstation.

CURRENT USES OF FMS

Flexible Manufacturing Systems are not now being used in the manufacturing sector of the U.S. economy. However, the various components of FMS, including robots and NC machines are becoming increasingly popular. The installed base of robots exceeds 5,000 and yearly sales are growing rapidly -- close to 50 percent per year by some estimates. A number of firms with varying backgrounds are currently striving for market share. Unimation, recently acquired by Westinghouse, and Cincinnati Milacron are the current market leaders, but many large firms from the machine tool electrical equipment and computer industries are joining the fray. These include General Electric, Bendix, General Motors, and IBM.

In contrast, machine tools have been a fundamental building block of the entire manufacturing sector for decades. The industry is very fragmented and is dominated by a few large suppliers and thousands of small firms. The industry has a low research intensity and has been characterized as being resistant to change. Indeed, major changes in technology have been attributed to outside sources -- changes in computer technology and the needs of large powerful buyers.

CHANGES IN TECHNOLOGY

The technology of machine tools and robots, as well as their integration into Flexible Manufacturing Systems share three common trends. First, there is an increasing need for sensors and measurement devices to provide the process control information needed to achieve cost reductions, quality improvements, and operation in an unmanned environment. Secondly, standards are needed so that FMS can be configured using robots and machine tools of various manufacturers. Standards are also necessary for robots, for example, between robot arms and grippers. Third, complex hierarchical control systems are needed for computers to link the activities of robots and machining centers into work stations and work stations into flexible cells.

AMRF

It is easy to see that these trends in the technology of FMS conform closely to NBS' traditional role, and to its recent activities in its automated manufacturing research facility. The AMRF is being developed and installed as a testbed for research in in-process (real-time) measurement and sensor systems. Standards must be developed which will allow machines made by different manufacturers to be compatible. Finally, control architecture must be developed to communicate instructions, store and retrieve data, and process information efficiently.

Thus, we have seen that NBS activity in its AMRF is well suited to supporting the productivity growth of the private sector in flexible automation. However, it is likely that FMS will fall short of its full productivity impact if the extent and sequence of the adoption of the various FMS options is suboptimal. An NBS role in the diffusion of FMS may also be an important factor in the total productivity impacts resulting from flexible automation.

DIFFUSION

Economic research has established that a number of economic variables can substantially influence the speed of diffusion of new technology. In particular, faster diffusion is associated with the expected profitability of the innovation, is negatively associated with higher required investment expenditures relative to firm size, and is likely to be faster in moderately concentrated industries. Although the econometrics literature has quantified the effect of these factors, they may be less important for the diffusion of FMS than factors internal to the firm such as fear of downtime and a general lack of critical information about FMS. These internal factors may substantially inhibit the diffusion of FMS. On the other hand, we believe that increased competition, particularly from firms in foreign countries, can be an important stimulus to diffusion. However, it is difficult to make a clear-cut assessment of the strength of the stimulus of international competition relative to inhibiting factors such as lack of information or to some of the more traditional stimuli to diffusion.

Gold and others have stressed the overriding importance for technology diffusion of the attitudes of influential management. Such attitudes will be of paramount importance due to the great lack of information that faces most firms in an adoption decision. If this view is correct in the FMS context, the lack of technical information may well be more important than factors like expected profits, in the sense that this factor will have a greater formative role in shaping managerial attitudes and decisions.

Foreign competition and the associated reduction in expected profits are nevertheless likely to be a predominant factor among users of FMS in the automobile and aircraft industries. Pressures from stockholders and boards of directors will undoubtedly raise questions about the security of their investment in the face of foreign competition. Moreover, pressures on the aircraft industry are also being applied by the Department of Defense due to its concern for quality and reliability. The adoption of FMS and other automation techniques seems likely to be a common management response. Furthermore, large firms will have the resources to acquire the information needed about automation technologies even if senior engineering managers are not at present familiar with FMS and its implications. On the other hand we expect that a lack of information and a fear of downtime will be the predominant influence in the market segment made up of small machine shops. Such firms in some cases will be privately held and frequently will not possess the in-house expertise or resources to make a thorough analysis of the costs and benefits of adopting alternative FMS strategies.

The acquisition and evaluation of credible information by potential users will be very important for the diffusion of FMS. Aggressive marketing will hasten diffusion, but aggressive sales efforts may be oriented mainly toward the near-term installation of robots and other hardware rather than providing users with a credible long-run blueprint to automation. This type of sales effort is unlikely to facilitate the long-run diffusion of FMS or the maximum productivity gains that FMS can bring.

In this context, foreign competition on the supply side of the FMS market may have a favorable influence on diffusion. Foreign firms interested in selling FMS hardware may well perceive the acute information needs of potential FMS customers and respond accordingly, particularly when these foreign firms are well capitalized and are following a strategy that emphasizes long-run growth. On the other hand, small, under-capitalized machine tool firms in the United States may be forced by their financial circumstances to rely more on a short-run strategy of maximizing near-term equipment sales. If adopted, this strategy may lead to the types of sales efforts that will inhibit FMS diffusion and productivity impacts.

The adverse effects of overly aggressive sales efforts by equipment suppliers can be mitigated somewhat if potential FMS users have ready access to credible information that compares and contrasts various FMS hardware configurations. Ideally, this information would be made available by an industry trade association, government agency, or consulting firm widely known for its objectivity and expertise in the area. NBS is one possible source for the kind of information that will be needed. CRA's (1983) report to NBS points out that NBS can be particularly effective in supplying such information because it is likely that FMS suppliers and adopters would perceive NBS as a neutral expert and value the impartiality and thoroughness of the FMS research done there.

METHODOLOGIES FOR FORECASTING DIFFUSION RATES

The ability to forecast with some precision the rate of diffusion of FMS technologies would be an important component of forecasts of the overall productivity impacts of FMS technologies. However, data limitations and other factors will make it exceedingly difficult to forecast the diffusion of FMS technologies using statistical techniques, such as econometrics, that rely on historical data. The following limitations are the most serious:

- The future will not be like the past due to the rapidly growing influence of international competition on diffusion;

- Both FMS technologies and the populaton of potential adopters will change rapidly and these changes will add considerable complexity to the specification and estimation of forecast equations; and

- The literature we have examined suggests that many factors influence diffusion beyond those usually included in econometric analyses of diffusion.

These three limiting factors will lead to a wide range of estimates of the rate of diffusion of FMS technologies and thus would lead to a wide range of estimates of the productivity impacts of FMS technologies. Each of these factors is now discussed.

INTERNATIONAL COMPETITION

Probably the most important factor that supports our conclusion regarding the difficulties of precisely forecasting the rate of diffusion of FMS technologies is that the past is an uncertain and sometimes misleading guide to the future. Most reports on FMS and other technology-based areas reflect a growing concern about the increasing importance of international competiton.

None of the econometric studies that we have examined reflects international competition in the set of explanatory variables utilized. Variables representing industry structure may capture some of the effects of increased international competition, but we believe that increasing international competition will influence the diffusion of industrial technologies in ways that cannot be fully captured by measures of industry structure.

The current apprehension about international competition held by many businessmen and policymakers is that foreign nations, particularly Japan, are mobilizing entire industries to work in a coordinated fashion to capture a leading position worldwide in FMS technology and other key technologies. How successful these joint efforts to develop targeted technologies will be and what effects international competition may have on the rate of diffusion of new technologies among U.S. firms is uncertain. On the one hand, the threat or presence of foreign competition may stimulate U.S. firms to develop and adopt new technologies at a faster pace. On the other hand, if U.S. firms fall too far behind in the technology race, they may not survive long enough to develop or adopt new technology. Whatever the future effects on diffusion resulting from intense international competition turn out to be, though, they are not likely to be captured in an econometric forecasting model.

RAPID TECHNOLOGY CHANGE

Rosegger, Gold, Abernathy, and others have criticized econometric models of diffusion for not adequately dealing with the phenomenon of the technology undergoing continuous improvements at the same time it is being diffused. Furthermore, the markets for new industrial technologies are likely to be expanding as technical improvements are made. Therefore, an accurate forecast of diffusion rates has to examine the changing technical characteristics of the equipment whose diffusion is being forecasted thoroughly enough to be able to identify the various populations of potential adopters and to differentiate the costs and benefits of adopting the technology for each population at each point in time. Such an analysis combines a technology assessment and a market assessment and is likely to require substantial resources.

OTHER FACTORS

Econometric approaches also have difficulty taking account of the many influences on diffusion that are internal to the firm. In the FMS context, factors such as fear of downtime and of obsolescence are likely to be as important or more important than some of the variables econometric studies have found to be significant in explaining diffusion.

A lengthy list of internal factors found to influence diffusion was presented in Table 7-2. Internal factors such as firm size and firm R&D expenditures can be quantified and included in econometric and other forecasting models. However, the following internal influences on diffusion will be difficult to specify quantitatively.

- Fear of downtime;
- Work flow reorganization required;
- Internal firm structure;
- Knowledge of senior managers;
- X-inefficiency; and
- Personality of the firm.

Even if such variables can be specified quantitatively, it will be very difficult to obtain data to estimate regression coefficients for them.

CONCLUSIONS AND RECOMMENDATIONS ON FORECASTING

Developing accurate forecasts of the rate of diffusion for specific classes and vintages of FMS equipment will be very difficult. However, productivity impacts cannot be estimated without some estimates of or assumptions about the timing and pattern of diffusion. If a forecast of the diffusion and productivity impacts of a class of FMS technologies is to be made by NBS, we recommend that it include careful cost engineering work, preferably by class of plant. Furthermore, efforts should be made to identify the various segments of potential adopters and to gain an understanding of the influences internal to the firm that are likey to be important for diffusion in each segment. Such factors can best be identified through plant surveys. However, trade associations may be able to supply some of the required information in a cost-effective way. Understanding the internal factors and the cost engineering tradeoffs will substantially increase the accuracy of a diffusion forecast.

Where data limitations preclude the use of econometric forecasting approaches, survey methods such as Delphi questionnaires or sequenced interviews might be utilized. Such techniques can be employed at the level of market segments, and would allow a researcher to learn about the internal as well as external influences on diffusion. Above all, we recommend the avoidance of statistical approaches that rely heavily on data that are considerably aggregated. SIC data that aggregate many distinct industries and market segments should not be used if forecast accuracy is important.

IMPLICATIONS FOR THE ROLE OF NBS IN THE DIFFUSION OF FMS TECHNOLOGIES

Rapid diffusion of FMS technologies requires potential users to have competent, unbiased, and comprehensive information concerning the performance characteristics of the various types of automation equipment. Information is also required about the organizational and productivity consequences of the alternative scenarios for purchasing and installing such equipment, and about the technology trends in equipment and systems that will determine how long a particular FMS installation will be technologically and economically competitive. Large segments of potential FMS users in the United States lack the engineering talent and other resources to develop efficiently the required information on their own.

NBS is likely to develop substantial expertise on the suitability of various types of FMS equipment for various industrial applications as a byproduct of its research on FMS standards and measurement. Such information could expedite the diffusion of FMS technologies if it is aggressively disseminated. NBS' role in dissemination would stop short of its becoming the Consumer Reports of the FMS industry, and of course the agency would maintain its traditional neutrality with respect to products of different vendors. Rather, NBS might develop and disseminate generic information concerning performance characteristics or the consequences of adopting specific classes of equipment. Moreover, NBS could possibly provide laboratory test structures through which potential users could gain direct-contact experience, thereby advancing their understanding of both their needs and the feasibility of different versions of the generic technology.

In this role, NBS would increase the capacity of potential users to acquire and use more product-specific information on FMS technologies, but would not directly supply product-related data on which firms would base their adoption decisions.

Finally, NBS might attempt to tailor its provision of information to the particular needs of various segments of the population of potential users. For example, small firms that might use FMS are unlikely to be as familiar with the computer and electronics associated with FMS as they will be with the mechanical aspects of FMS. Furthermore, these same firms are probably more receptive to oral channels of communication than to written ones. These two characteristics of small potential users suggest that regional workshops, or direct-contact opportunities at the AMRF, on the electronic aspects of alternative FMS options might be particularly beneficial. Diffusion would be accelerated by such workshops or contacts because users would have the opportunity for face-to-face interaction with respected and credible sources of technical information such as NBS staff, as well as hands-on experience with equipment. Secondly, we have noted that diffusion will be impaired if senior engineering managers in large firms are not sufficiently familiar with the full corporate ramifications of a transition to FMS. To close this information gap NBS might consider holding a series of industry-specific workshops. Each workshop would focus on the implications of alternative FMS technologies for a particular industry and stress the implications of FMS for production processes in that industry.

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

The basic elements of flexible manufacturing system (FMS) technology are described and assessed in terms of their productivity growth potential. Measurement-related elements are emphasized. The economic factors affecting the development and diffusion of the FMS technology are then identified, including the role and contributions of the National Bureau of Standards. Emphasis is given to the factors determining the rate of diffusion of systems technologies such as FMS. Some of the literature on technological diffusion is reviewed and implications are drawn for the role of NBS.

One of the most important factors affecting the productivity potential of systems technologies such as FMS is the system control hierarchy. The control structure provides feedback on system performance and uses this information to enable different components to interact effectively, thereby resulting in maximum productivity gains. Moreover, individual component productivitity is dependent on accurate techniques for real-time measurement of the operating environment. The unavailability of such measurement-related "infratechnologies" reduces potential productivity gains and introduces uncertainty on the part of buyers, thereby showing diffusion and thus realized productivity gains. Diffusion is further slowed by the lack of standardization of the interfaces between components. The absence of standardized component interfaces increases risk to potential buyers because they will not have the flexibility to purchase components from different manufactures and easily integrate them into the desired FMS.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

Automation; government; industrial growth policy; innovation; productivity; standards; technological change; technological diffusion;

13. AVAILABILITY

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